Updates on a two-habit model for the optical properties of ice clouds

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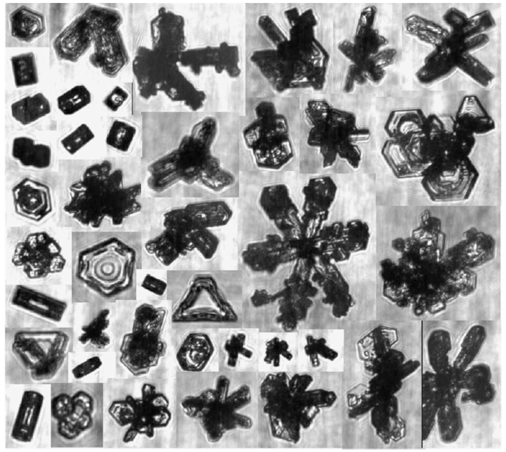
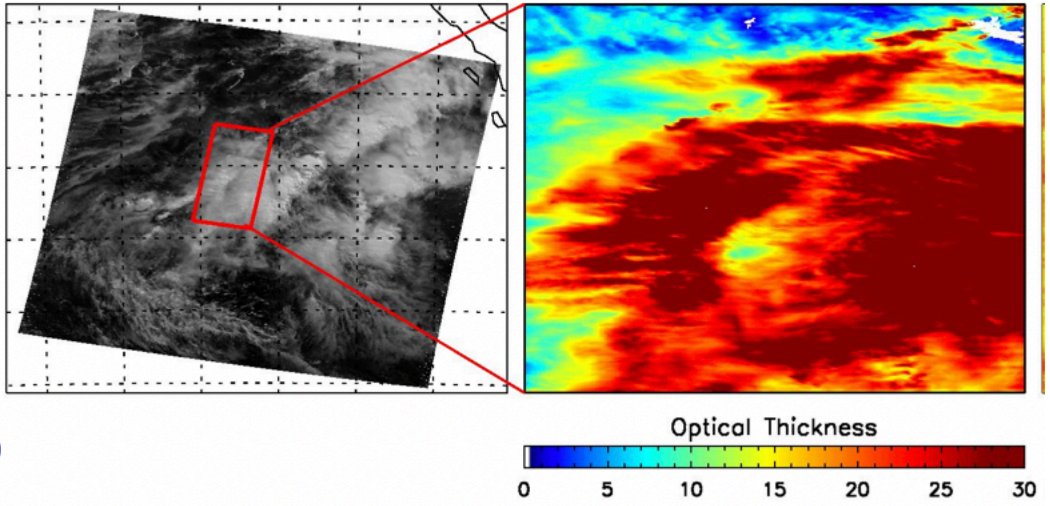
Importance of Ice Cloud Particle Models



Bailey & Hallett (2009)

Ice particle model
(for generating look-up tables
in remote sensing applications)

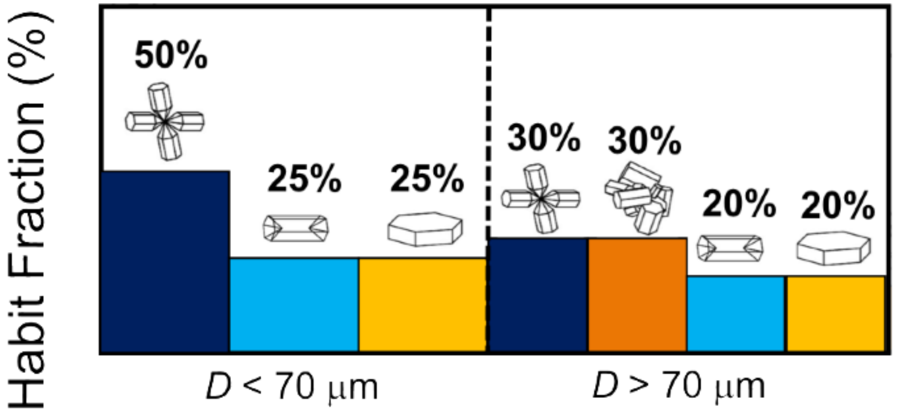
Yang et al., 2008



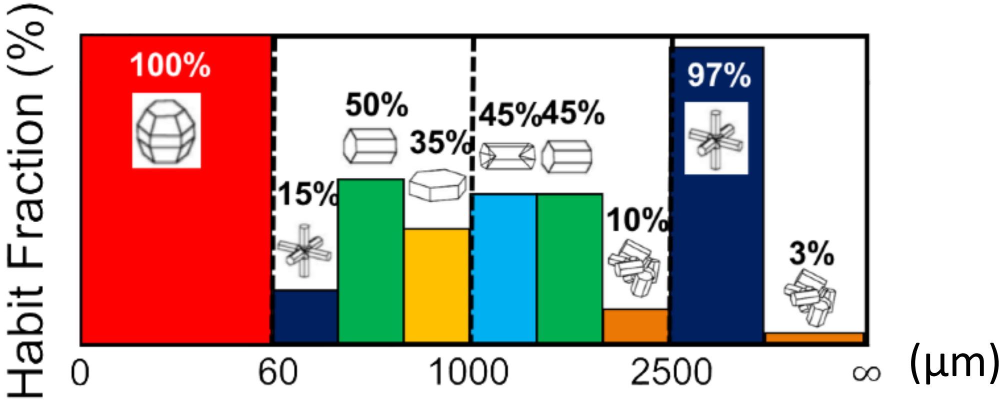
- Ice clouds cover $\sim 20\%$ of the Earth and thus influence both the Earth's climate system (Liou and Yang, 2016).
- Ice clouds are still least understood from remote sensing and radiative transfer perspectives due to uncertainties in ice cloud microphysical and optical properties.
- An Ice cloud particle model is needed to describe the microphysical properties (e.g., particle habit) and optical properties (e.g., the scattering phase matrix) of ice clouds.
- The single-scattering properties are fundamental to applications in remote sensing and radiative transfer simulations involved in radiative forcing assessments.

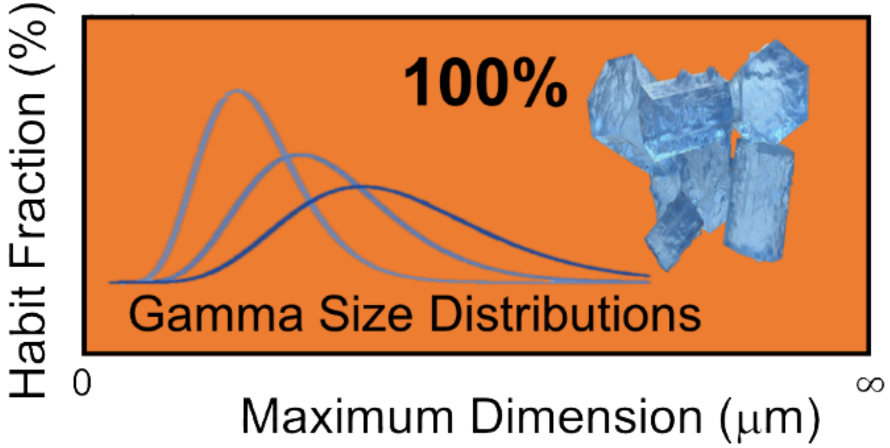
A brief history of the ice models assumed by the MODIS Science Team (King et al. 2004, Baum et al. 2005a,b, Platnick et al. 2016)

MODIS Collection 4



MODIS Collection 5



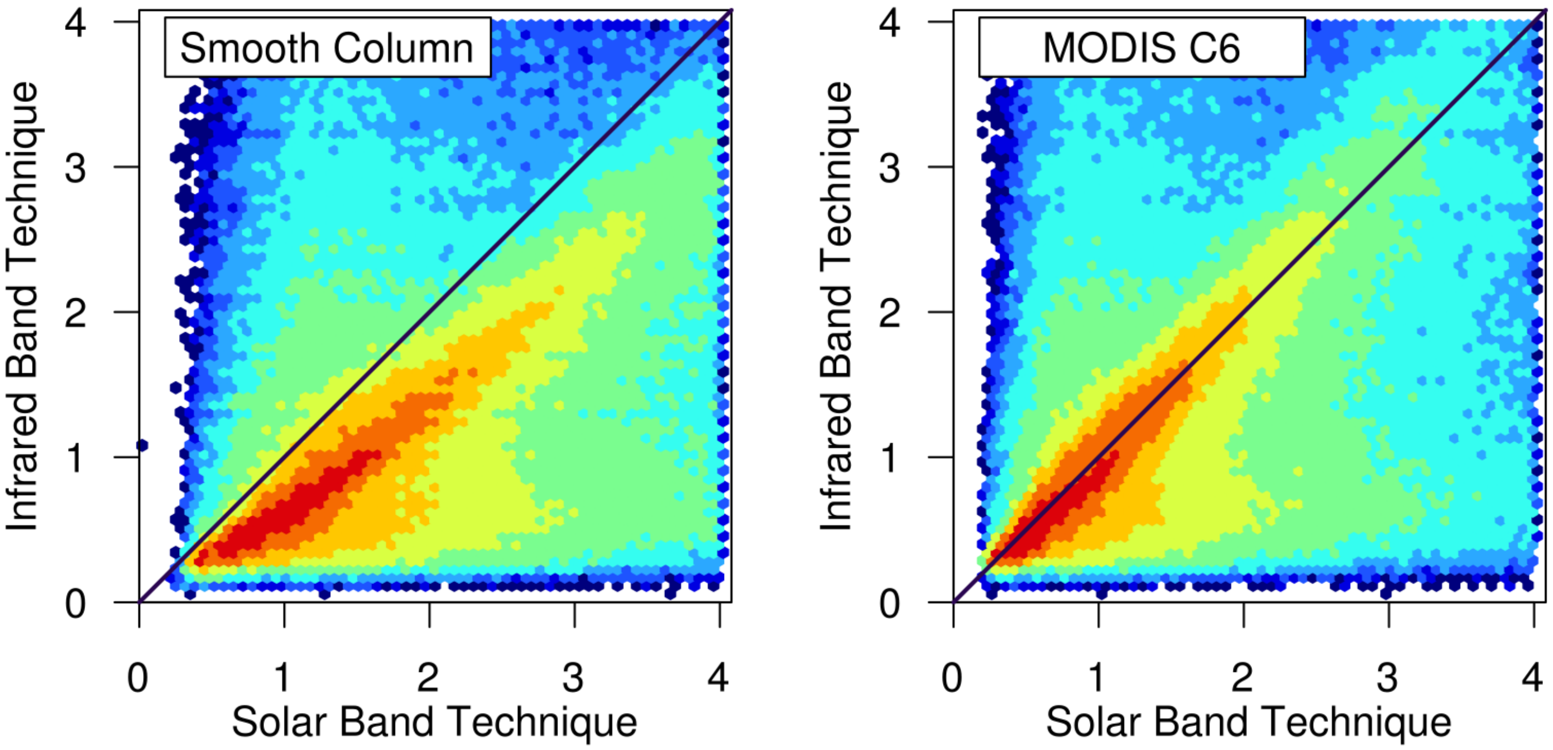


MODIS Collection 6

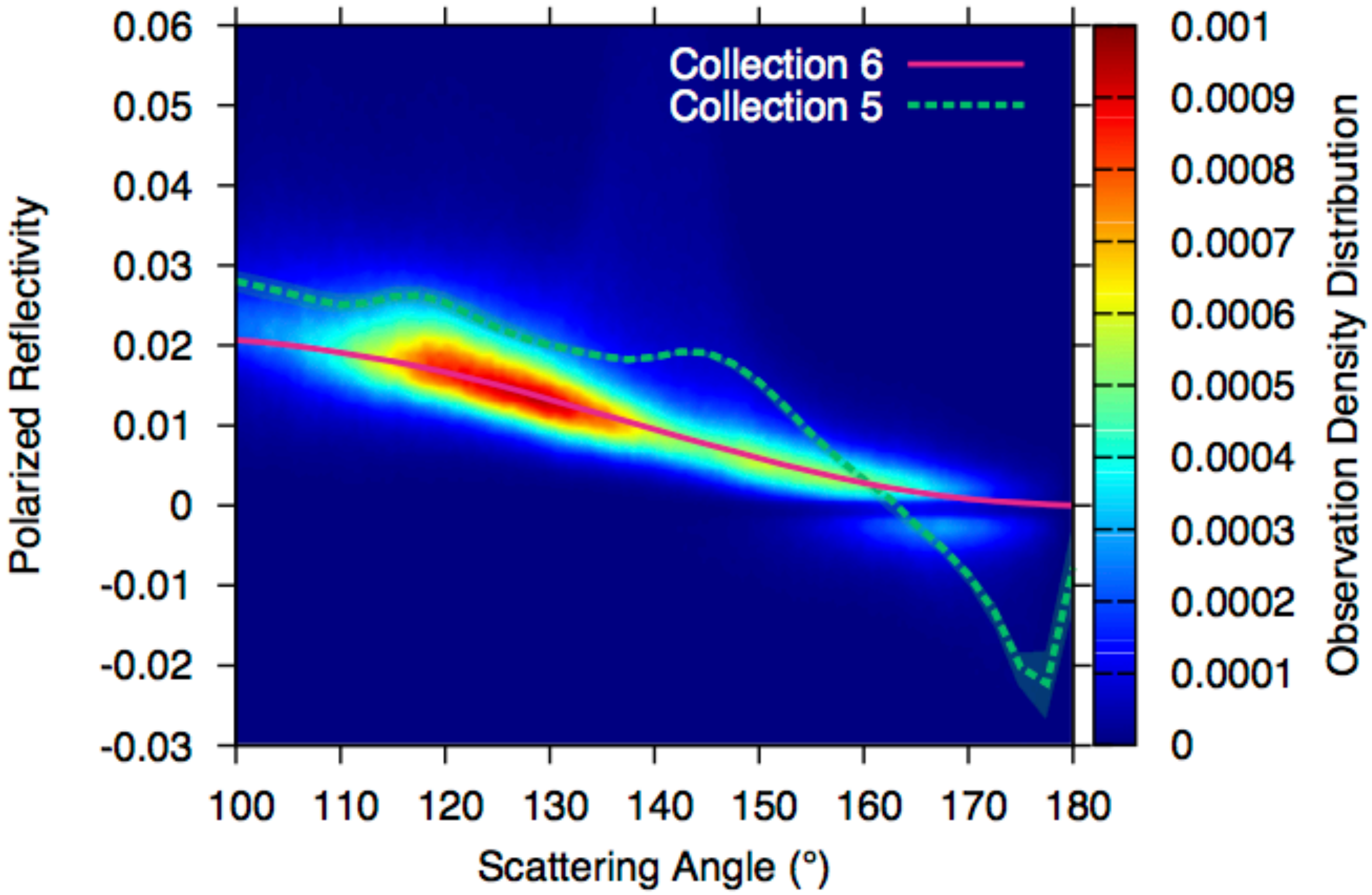
Spectral inconsistency/consistency of Ice cloud optical thickness values retrieved based on infrared bands and solar bands

Left panel: a smooth ice crystal model

Right panel: a rough ice crystal model (MODIS C6 model)



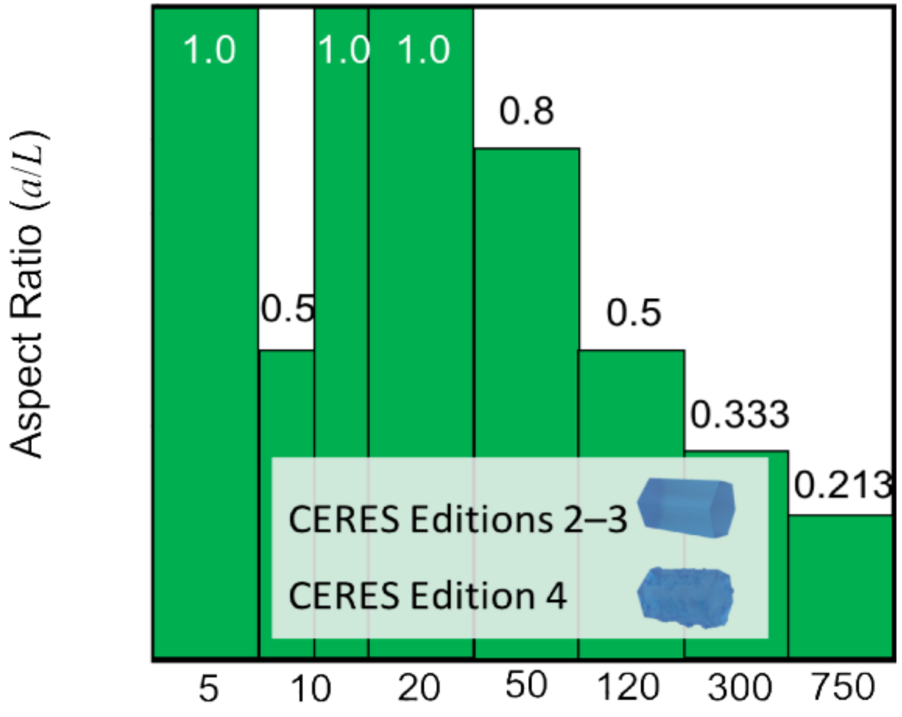
Inconsistency/consistency in polarimetric remote sensing applications



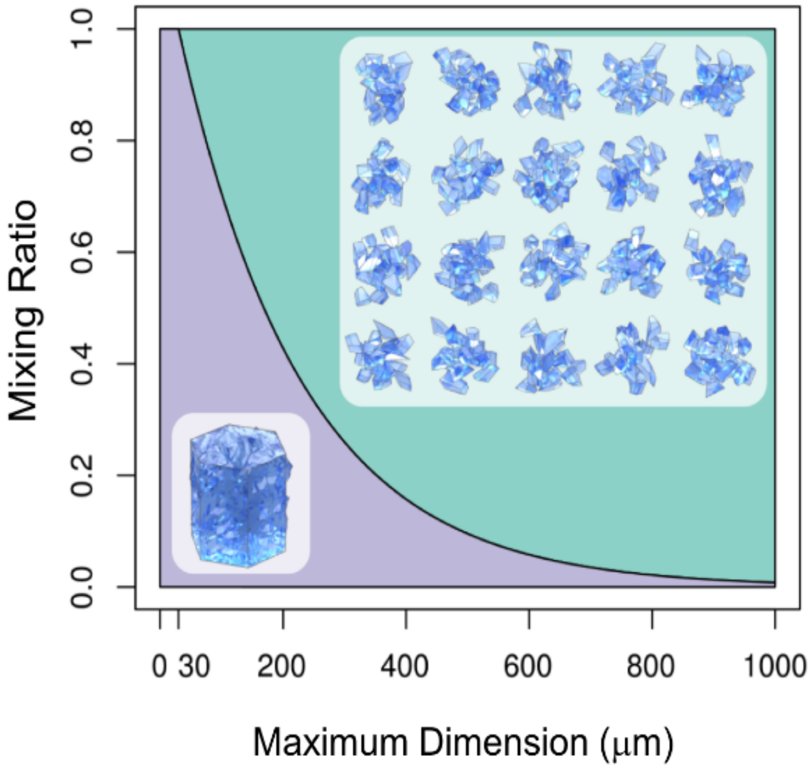
Observation density distribution of polarized reflectivity from the POLDER sensor and the theoretical prediction (MODIS Collection 5 and 6). Data are collected from cold ice clouds over Western Pacific in September 2005 (BT_{31} < 208 K).

A brief history of the ice models assumed by the CERES Science Team (Minnis et al. 2011, Loeb et al. 2018)

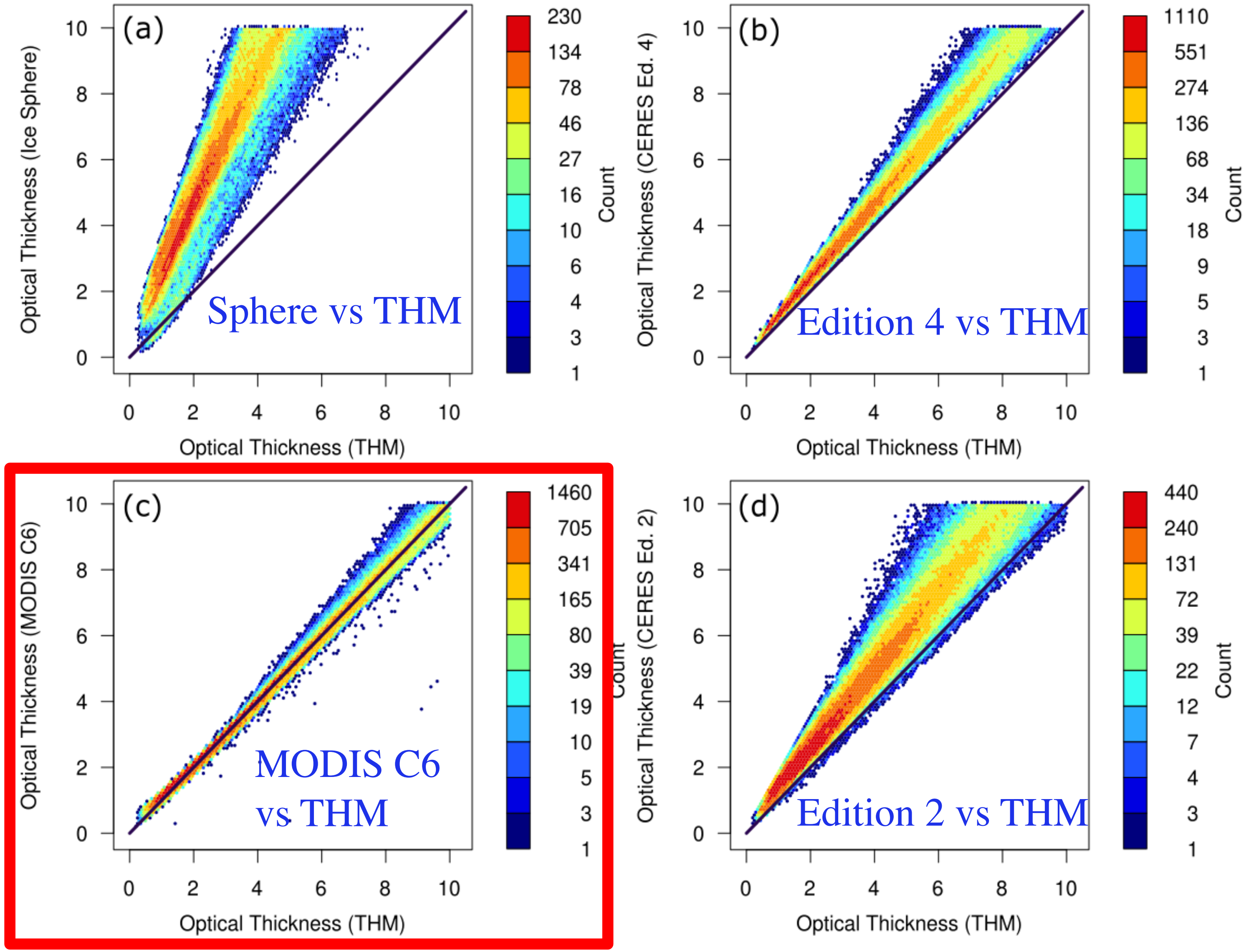
CERES Editions 2- 4



Future Edition 5

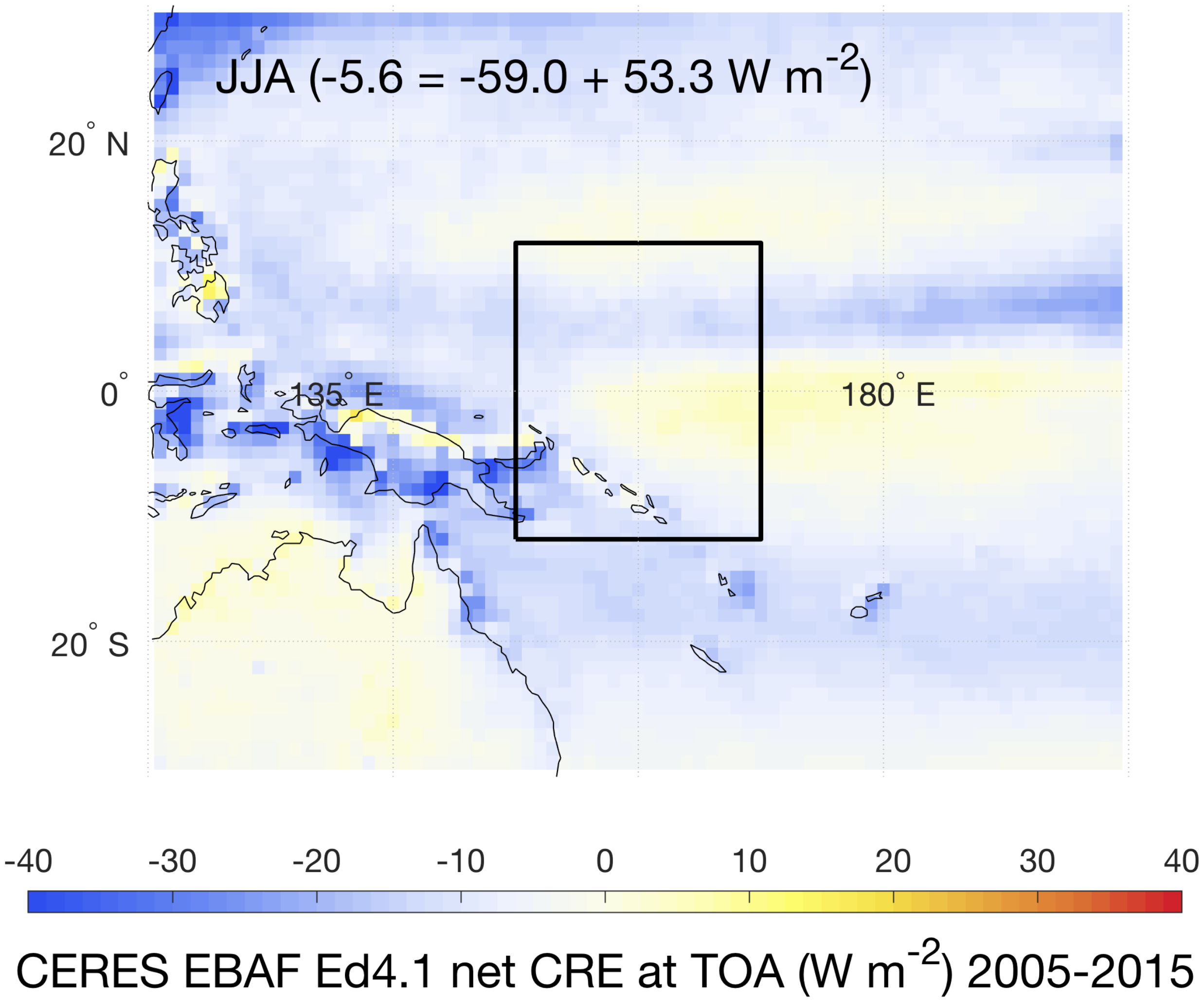


Note: The Edition 2 model is consistent with that assumed for the Fu parameterization of the bulk radiative properties of ice clouds, a default option in Langley's radiative transfer model.



Comparison of retrieved optical thickness values from the shortwave technique (shortwave bi-spectral method): (**a**) ice sphere and two-habit model (THM; potential CERES Edition 5 model); (**b**) CERES Edition 4 model and two-habit model; (**c**) MODIS Collection 6 model and two-habit model; and (**d**) CERES Edition 2 model and two-habit model.

CRE sensitivity to ice particle model



Dataset: CCCM one-layer ice clouds

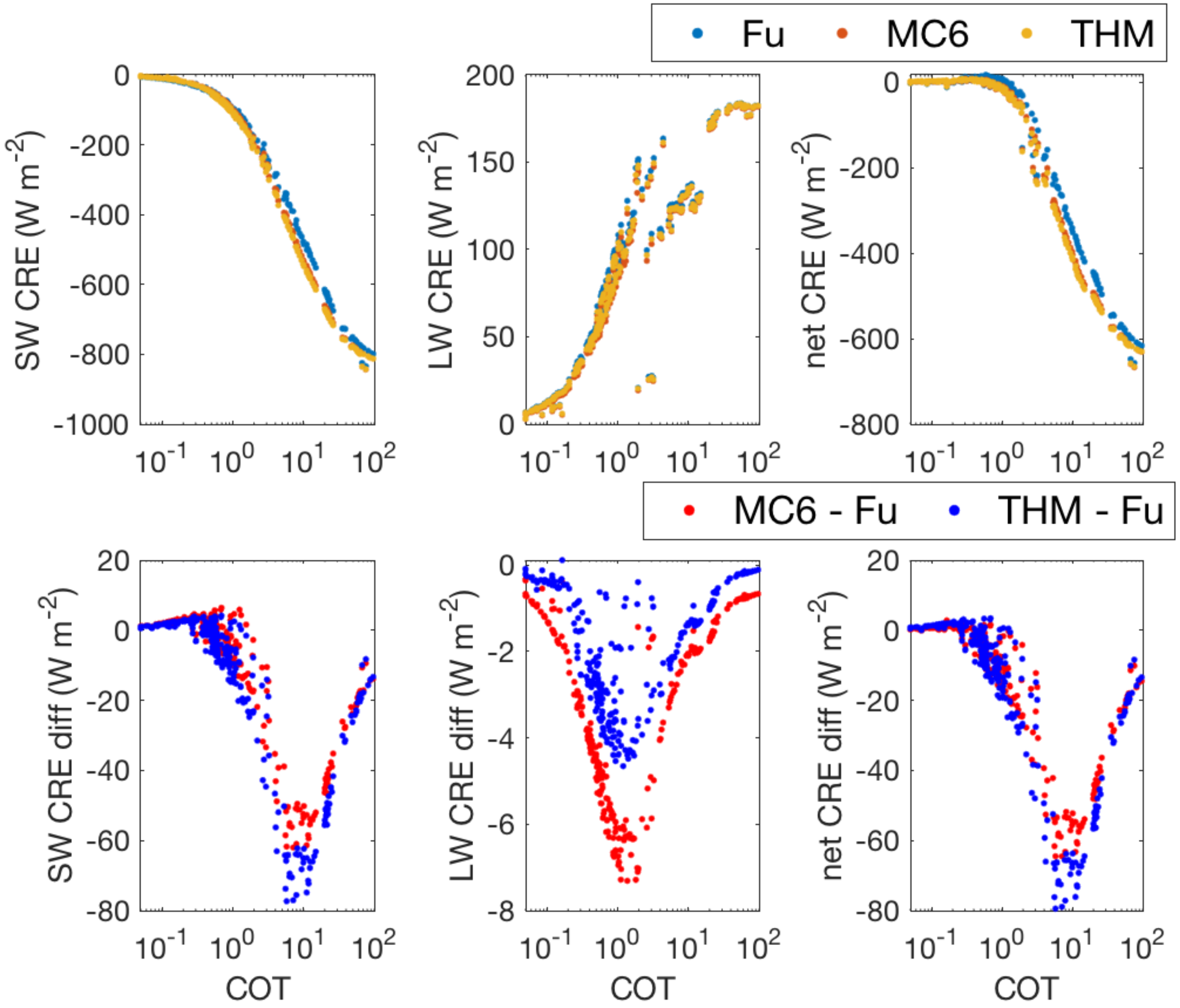
Time: July 31 2006, daytime

Location: Tropical Western Pacific Ocean (black box)

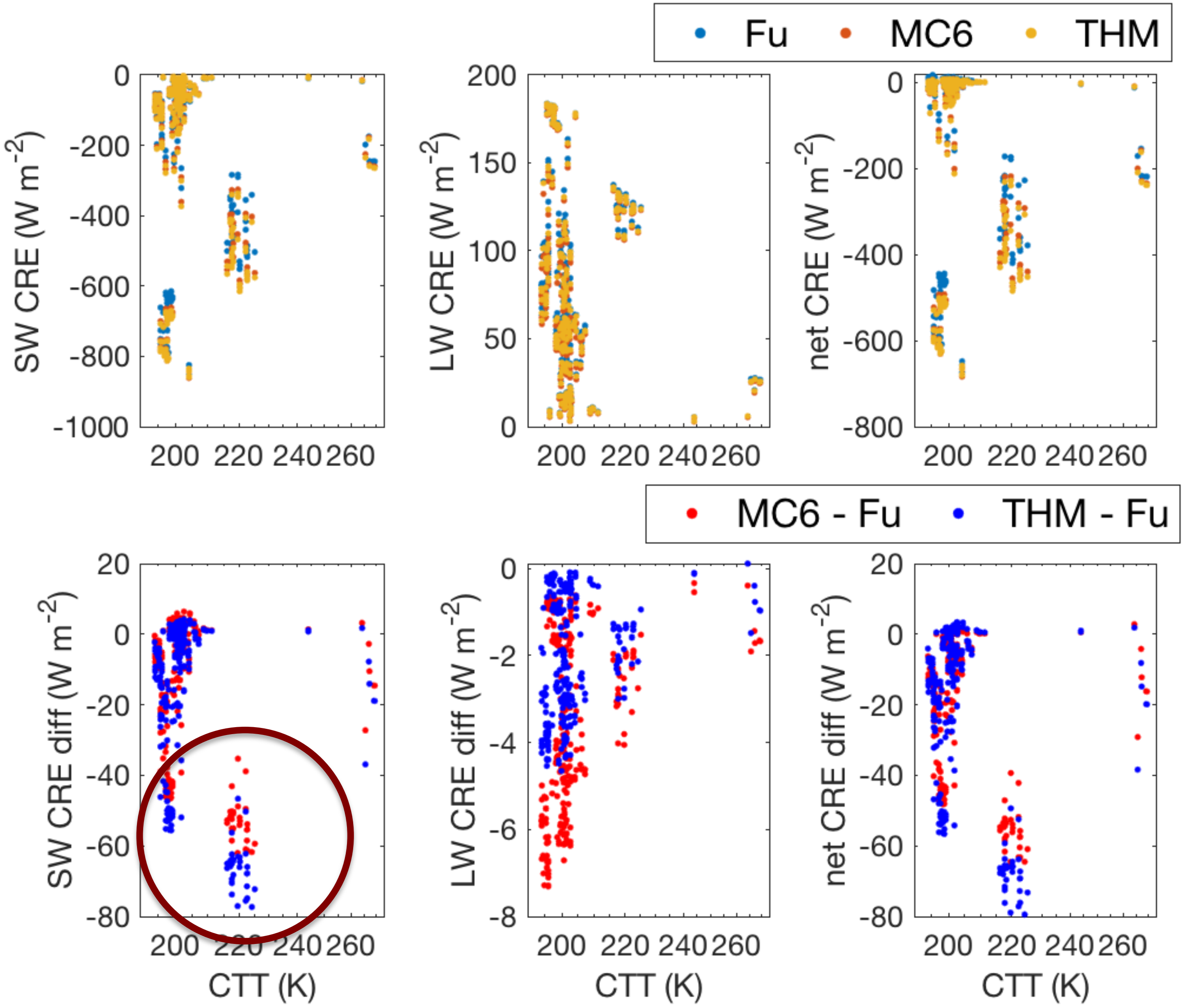
SW RTM: δ-16-stream DISORT RRTM_SW

LW RTM: RRTM_LW with inclusion of scattering effects (Tang et al. 2018)

SWCRE is more sensitive



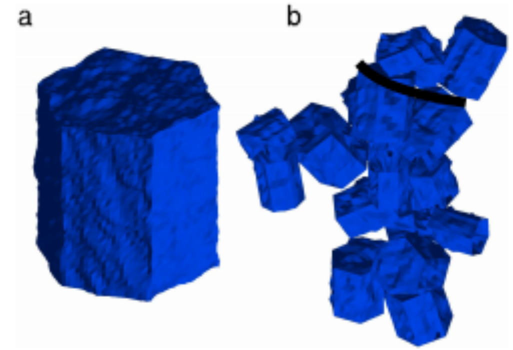
particularly when CTT ~ 220 K



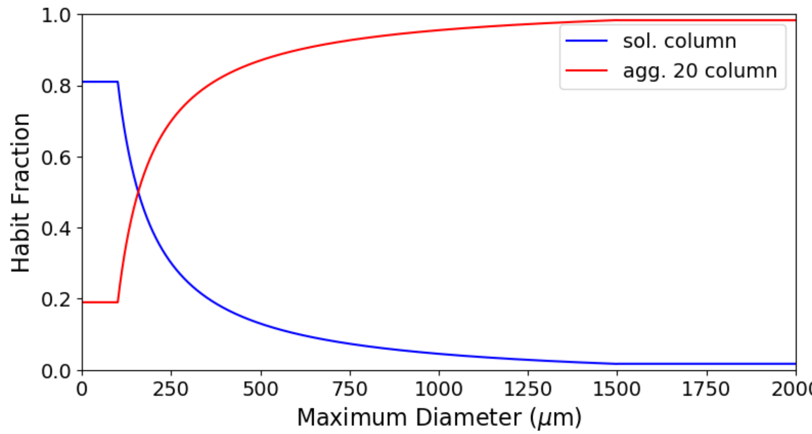
The History of the Two-Habit Model: 1st Version

- The 1st version of the Two-Habit Model (THM) was developed to serve as a replacement of the single hexagonal column habit model.
  - Natural ice clouds contain various particle habits and different habit preferences at different size ranges.
- THM based on the suggestion that atmospheric ice particles can be separated into two categories of particle complexity (Schmitt and Heymsfield, 2014):
  - "Simple" and "complex" particle geometries.
  - Complex particle habit fraction increases with increasing particle size.
- The 1st THM consisted of a severely roughened hexagonal column (simple) and 20-column aggregate (complex).
  - Particle roughness has significant influence on the optical properties and cloud radiative effect (e.g., smooth, featureless phase function).
- 1st THM showed excellent spectral consistency of retrievals of MODIS observations and could be used to represent ice cloud polarization properties (Liu et al., 2014).

1a



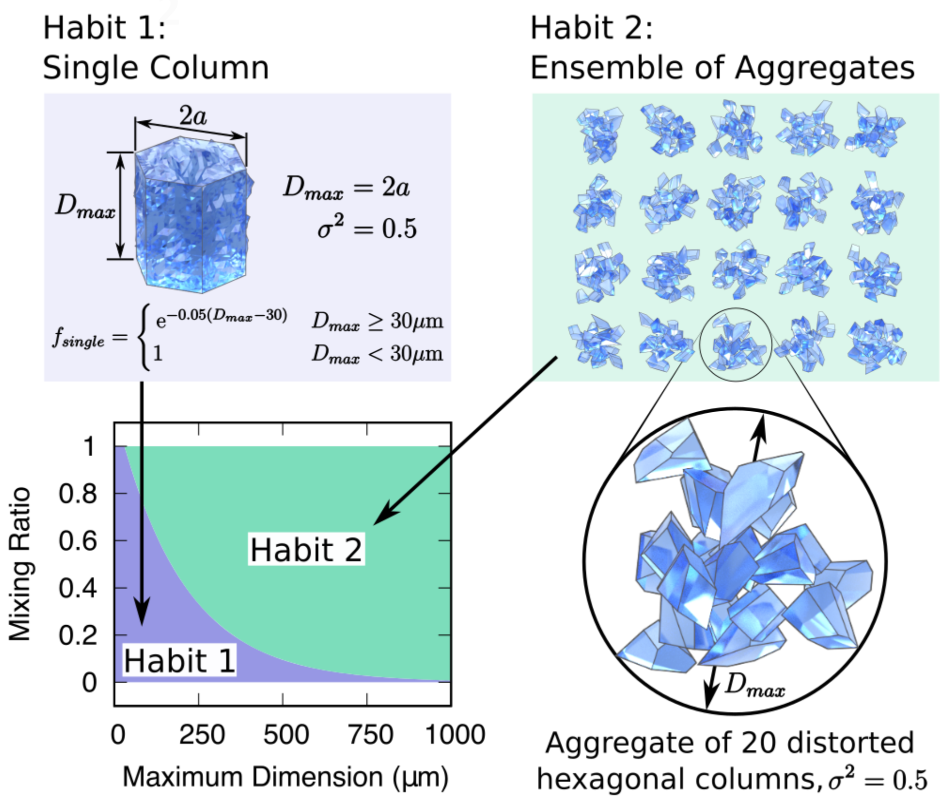
1b



1st version THM particle habits (1a) and habit fractions as a function of maximum dimension (1b).

The History of the Two-Habit Model: 2nd Version

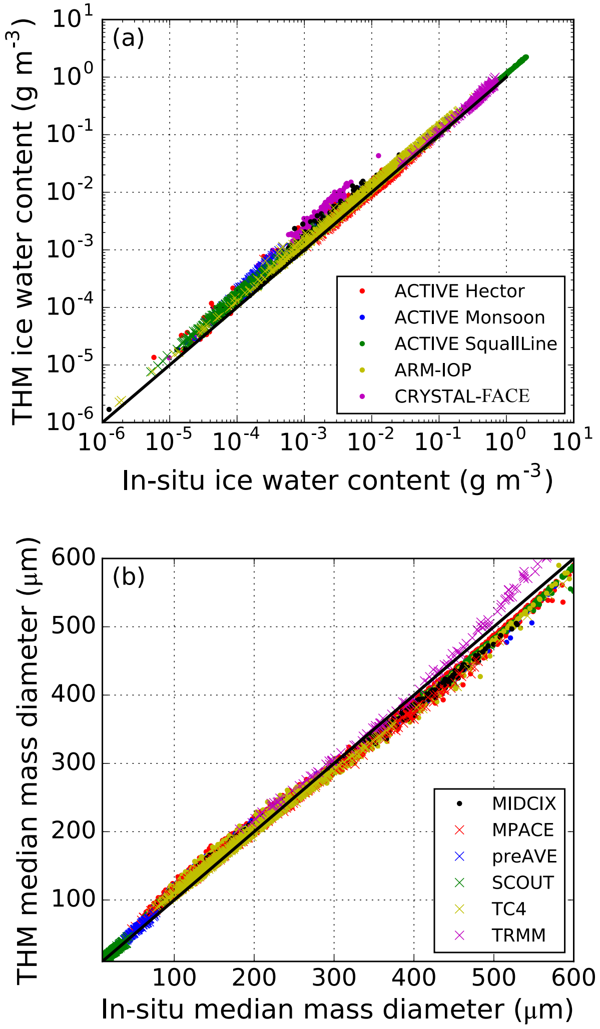
- The 2nd version of the Two-Habit Model (THM) was developed by Loeb et al. (2018) to examine the sensitivity of ice particle model assumption.
- The THM is improved by introducing an ensemble of irregularly-shaped particles to replace the severely roughened counterpart.
    - Effect of random distortion of an ensemble of particle shapes on light scattering computation equivalent to that of particle surface roughness.
    - 2nd version replaces roughened 20-column aggregate habit with 20-particle ensemble of irregularly-shaped 20-column aggregates.



2nd version THM particle habits and habit mixing ratio distribution as a function of maximum dimension.

Loeb, N. G., P. Yang, F. G. Rose, G. Hong, S. Sun-Mack, P. Minnis, S. Kato, S.-H Ham, W. L. Smith Jr., S. Hioki, and G. Tang, 2018: Impact of ice microphysics on satellite cloud retrievals and broadband flux radiative transfer model calculations. *J. Climate*, 31, 1851-1864.

Consistency of the model with in-situ microphysics measurement



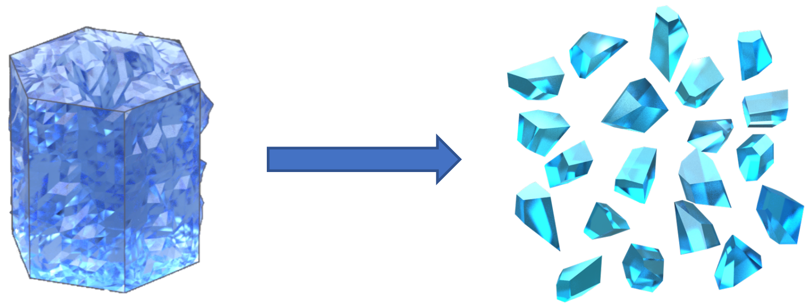
The 2nd version THM leads to mostly consistent theoretical ice water content and mass median diameter when compared counterparts measured during 11 field campaigns

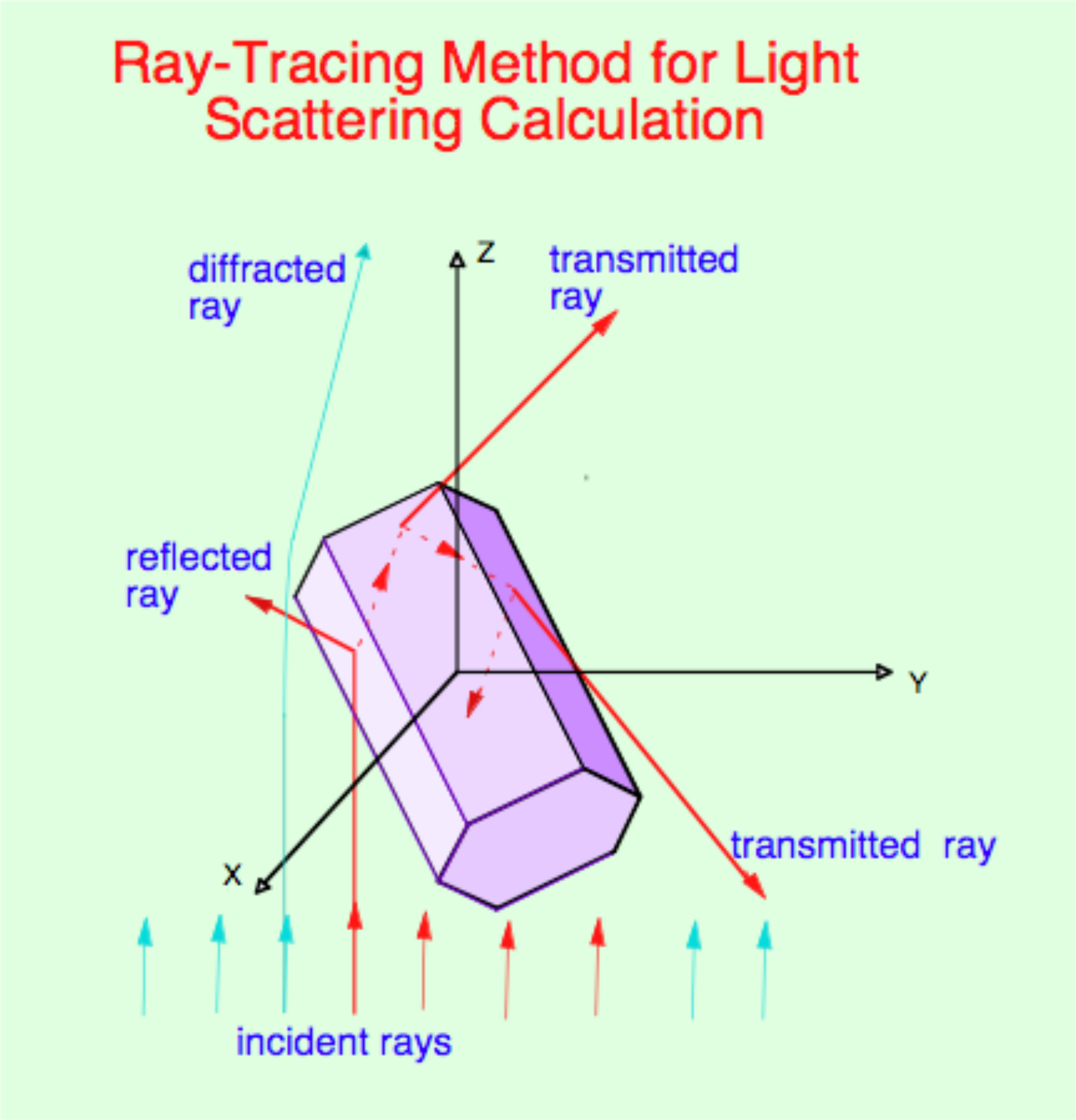
- Finding by Loeb et al. (2018): radiative fluxes derived using a consistent ice particle model assumption throughout provide a more robust reference for climate model evaluation compared to existing ice cloud property retrievals.

In other words, **the same ice model must be <u>consistently</u> used in forward remote sensing implementations and downstream radiative transfer computations.**

3^{rd} Version of THM: Changes/Improvements

- Building on what was done in the 2^{nd} version of THM, we introduce a 3^{rd} version of the THM with notable improvements.
  - Replace the roughened single hexagonal column with an ensemble of irregularly-shaped particles.
  - The overarching goal is to achieve consistency in active (lidar-based) and passive (imager-based) remote sensing applications.



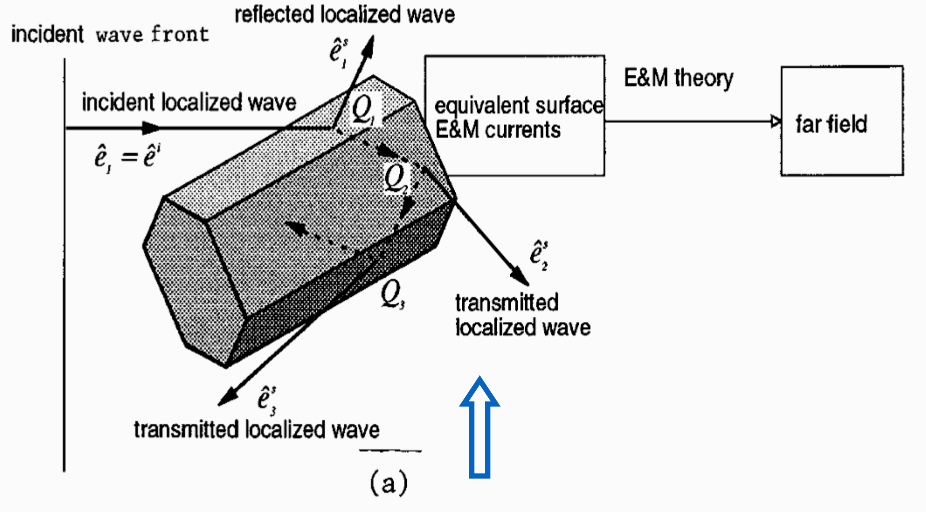


Conventional Geometric Optics Method (Cai and Liou, 1982; Takano and Liou, 1989; Yang and Cai, 1991; Macke, 1992).

Computationally efficient, but inaccurate particularly in the backscattering direction.

Physical-Geometric Optics Method (PGOM)—
Accurate but computationally inefficient

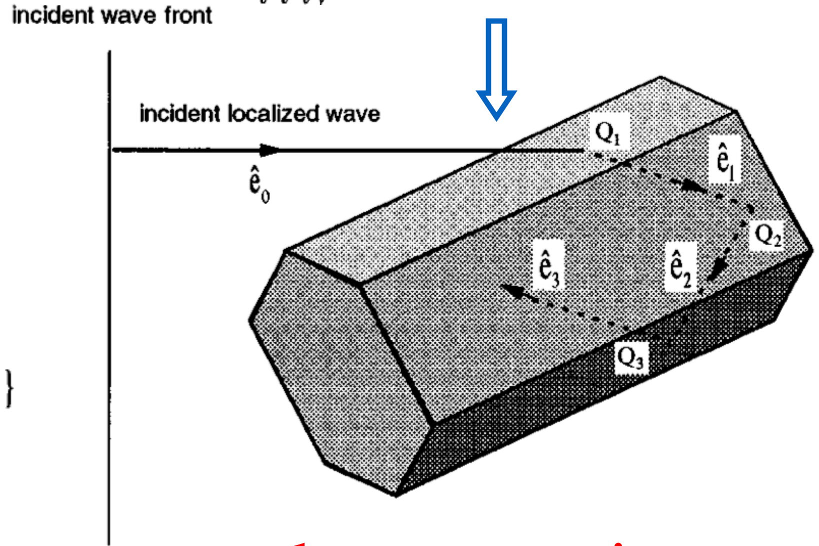
Yang and Liou (1996)
PGOMS – Surface-integral equation based



$$\mathbf{E}_s(\mathbf{r})|_{kr\to\infty} = \frac{\exp(ikr)}{-ikr}\frac{k^2}{4\pi}\mathbf{n} \times \iint_S \{\mathbf{n}_S \times \mathbf{E}(\mathbf{r}') - \mathbf{n} \times [\mathbf{n}_S \times \mathbf{H}(\mathbf{r}')]\} \times \exp(-ik\mathbf{n}\cdot\mathbf{r}')\, d^2\mathbf{r}',$$

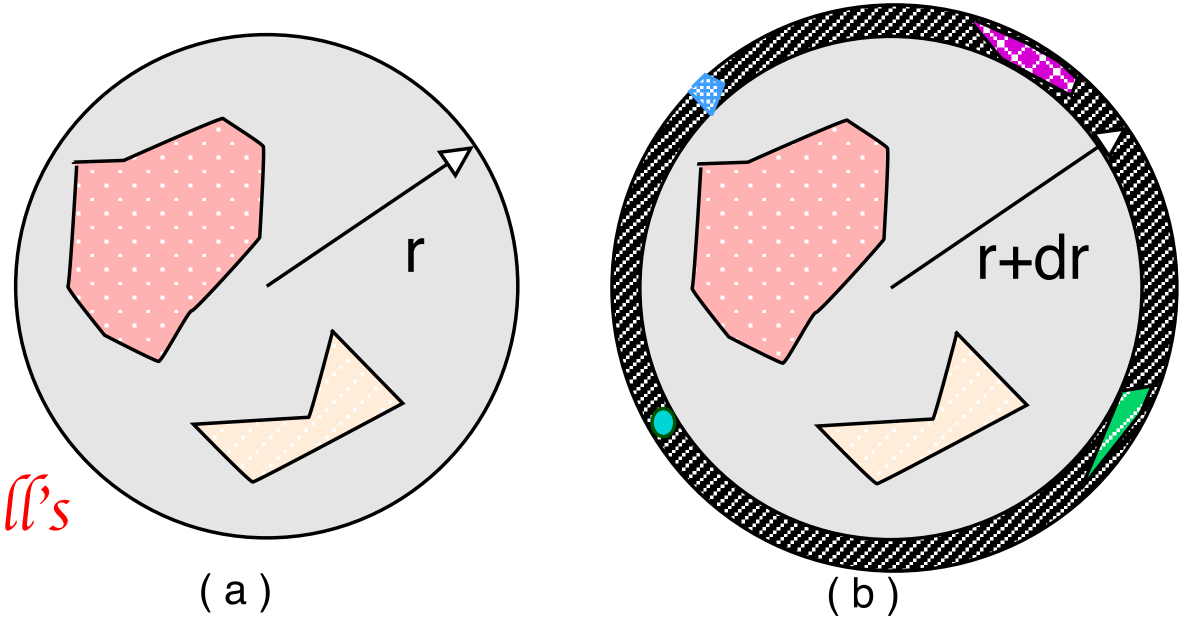
Yang and Liou (1997)
PGOMV – Volume-integral equation based

$$\mathbf{E}_s(\mathbf{r}) = \frac{k^2 \exp(ikr)}{4\pi r}\iiint_V [\varepsilon(\mathbf{r}') - 1]\{\mathbf{E}(\mathbf{r}') - \mathbf{n}[\mathbf{n}\cdot\mathbf{E}(\mathbf{r}')]\}\exp(-ik\mathbf{n}\cdot\mathbf{r}')\, d^3\mathbf{r}'.$$



New improvements by our research group using computer graphics techniques (Yang et al. 2019)

Invariant Imbedding T-matrix Method



Based on Maxwell's equations

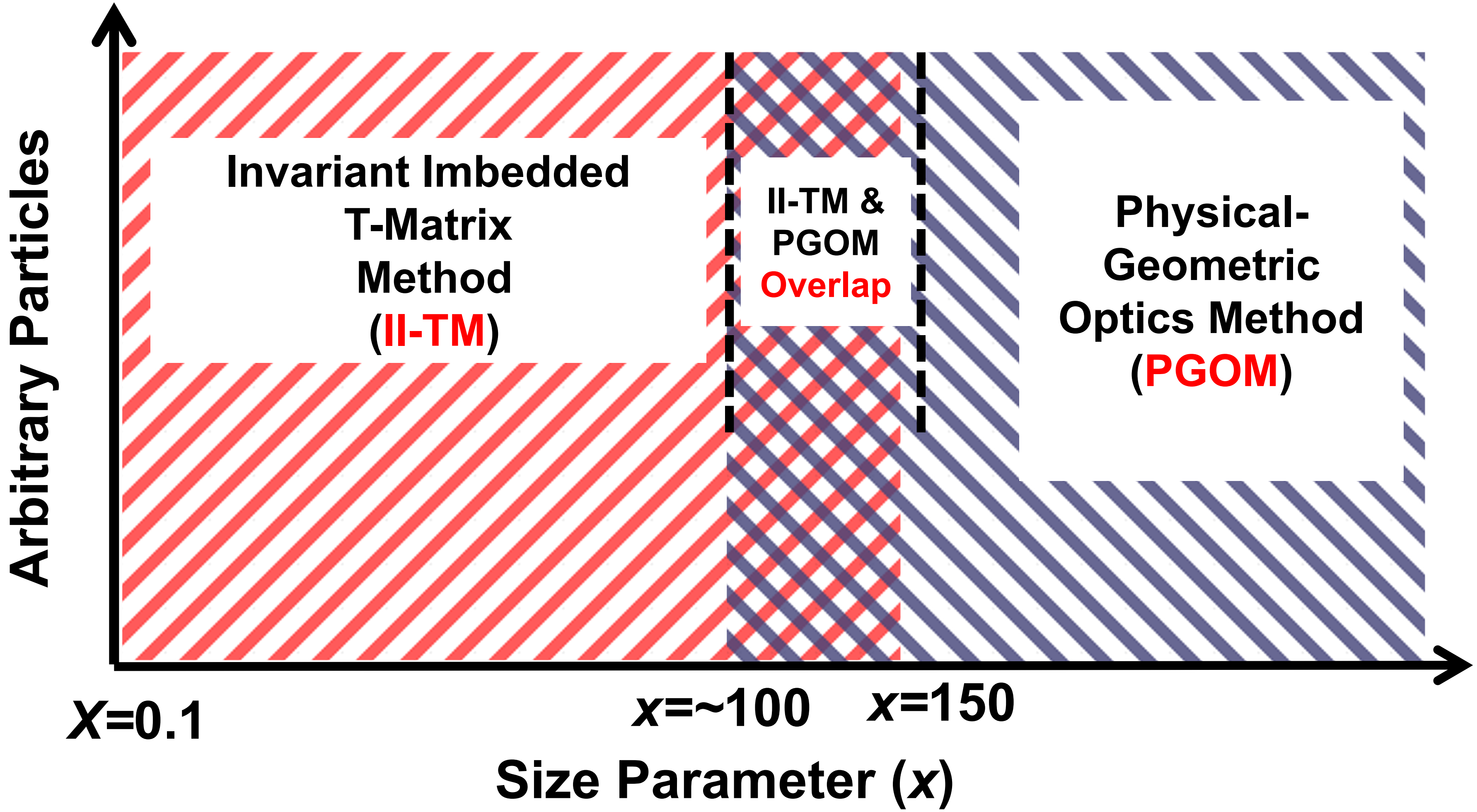
$$\vec{E}(\vec{r}) = \vec{E}_{inc}(\vec{r}) + k^2 \int \left(m^2 - 1\right) \vec{G}(\vec{r} - \vec{r}\,') \cdot \vec{E}(\vec{r}\,') d^3 \vec{r}\,'$$

Volume Integral Equation

$$\boxed{T_{mnmn'}(r+dr)} = Q_{11}^m(r+dr) + \left[\mathbf{I} + Q_{12}^m(r+dr)\right]\left[\mathbf{I} - \boxed{T_{mnmn'}(r)}\, Q_{22}^m(r+dr)\right]^{-1} \boxed{T_{mnmn'}(r)} \left[\mathbf{I} + \tilde{Q}_{12}^m(r+dr)\right]$$

Johnson (1988); Yang et al. (2019) and the references cited therein

Breakthrough: A combination of II-TM and PGOM can accurately cover the entire size parameter region (Yang et al. 2019)



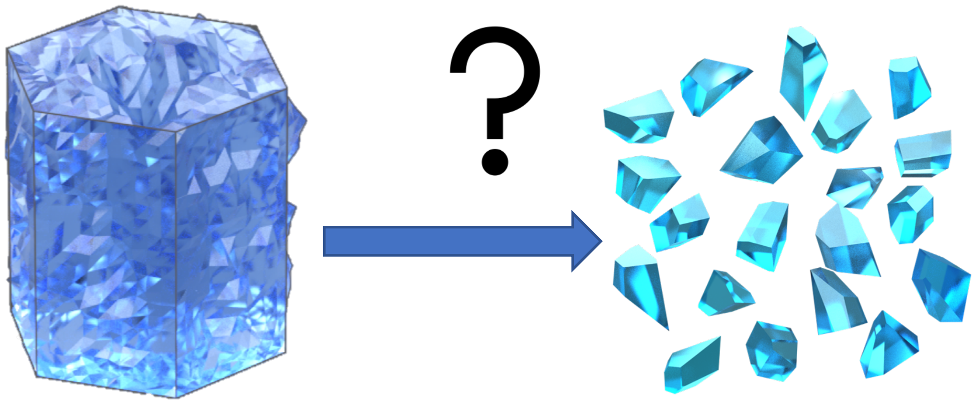
Improved Geometric optics method (IGOM)—based on mapping of the conventional ray-tracing method result

$$P(\theta) = 2\int_0^{\pi}\left\{[F_{11}(\theta,\theta_t)+G_{11}(\theta,\theta_t)]P_{conventional}(\theta_t)+[F_{12}(\theta,\theta_t)+G_{12}(\theta,\theta_t)]P_{12,conventional}(\theta_t)\right\}\sin\theta_t d\theta_t$$

- IGOM is less accurate than PGOM
- IGOM can be applied to a particle with small-scale surface roughness
- PGOM is not practical for application to a particle with small-scale surface roughness
- Unlike PGOM, IGOM is not accurate for backscattering computation

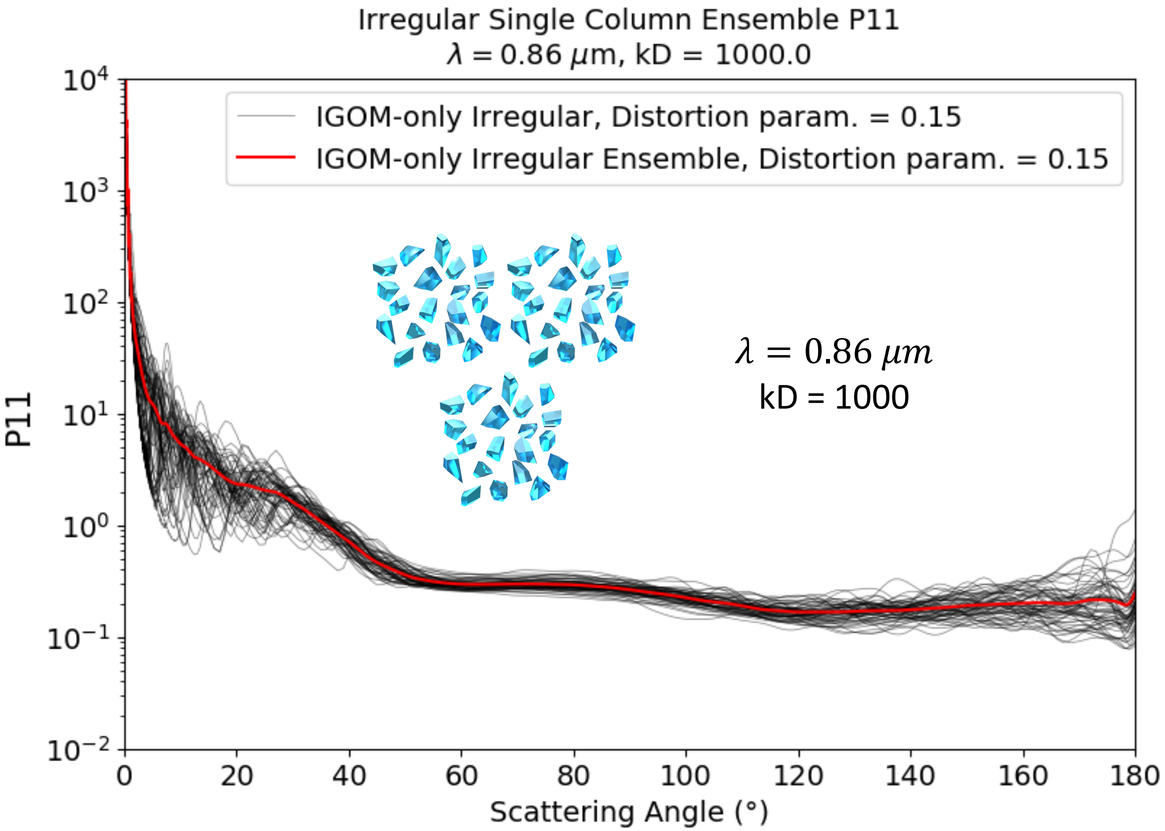
Use the PGOM ensemble-mean values of the optical properties of randomly distorted particles as surrogates of the IGOM results for a roughened particle.

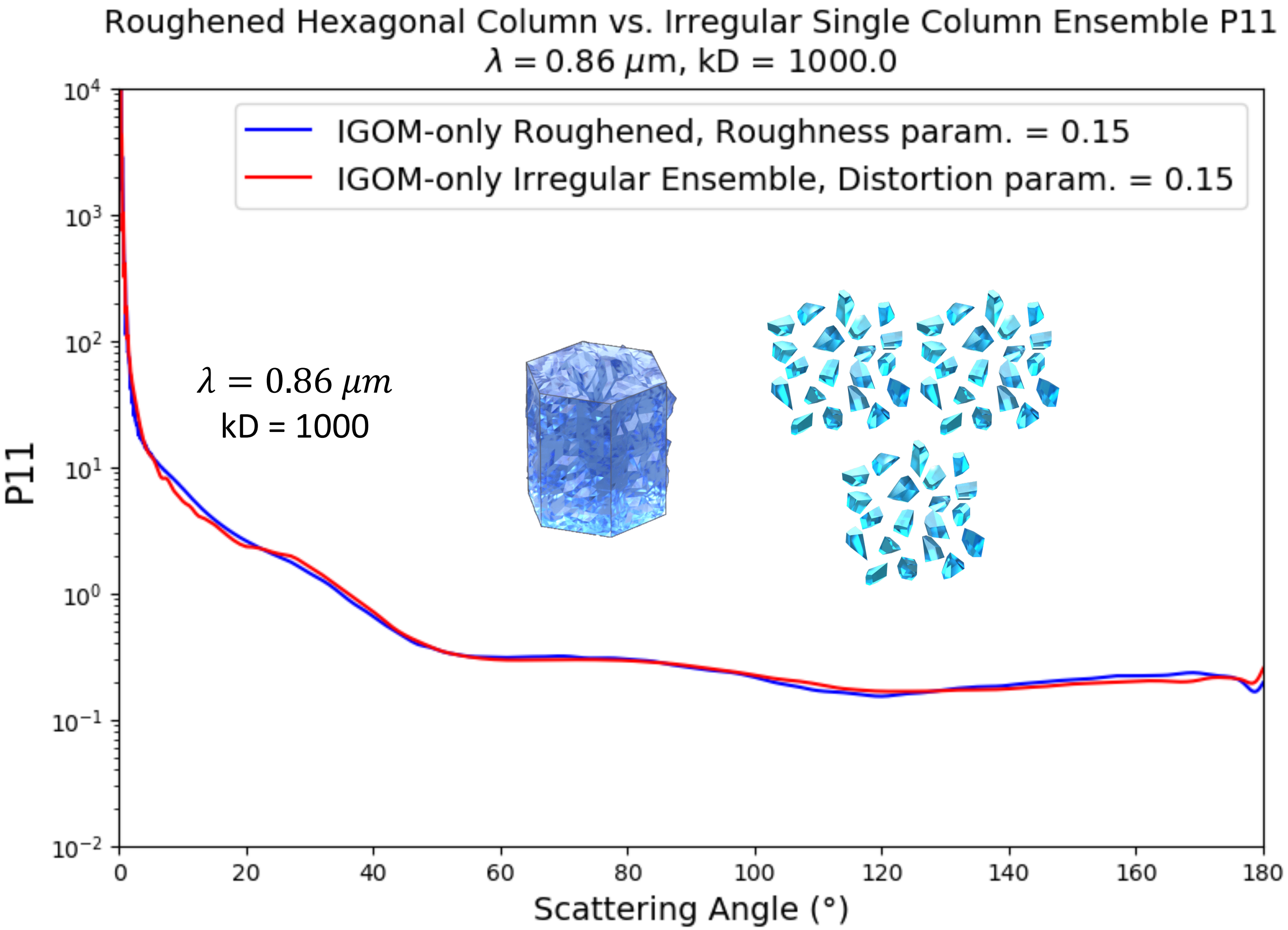
This hypothesis has been validated!



An Optimal Irregular Single Column Ensemble

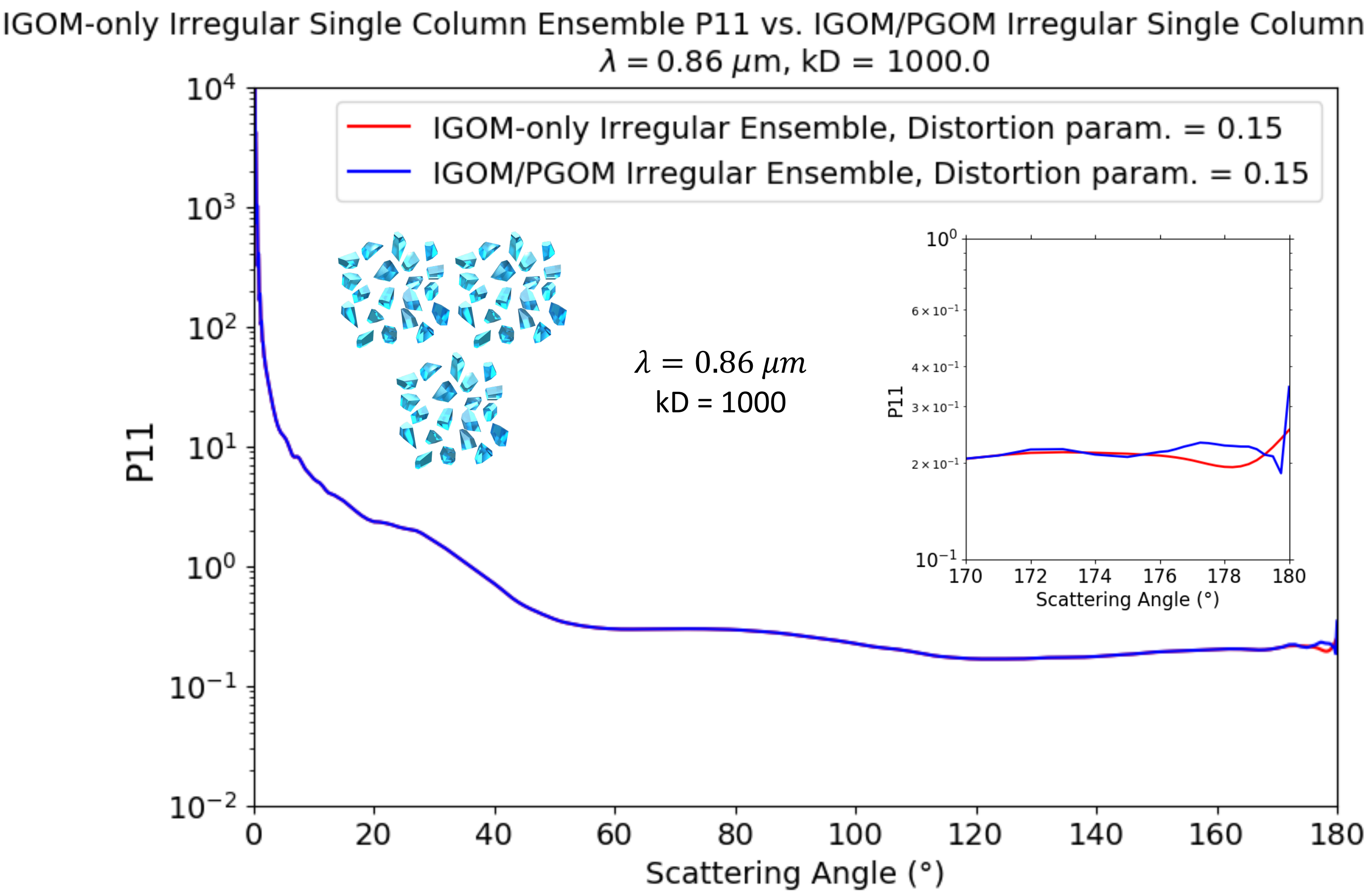
- From numerous randomly-generated irregular single column ensembles, we arrive at an optimal solution:
    - A 60-particle irregularly-shaped single column ensemble.
    - Transition maintains P_{11} smoothness and consistency with roughened hexagonal column for moderate/large size parameters.





PGOM-enhanced Backscattering Calculations

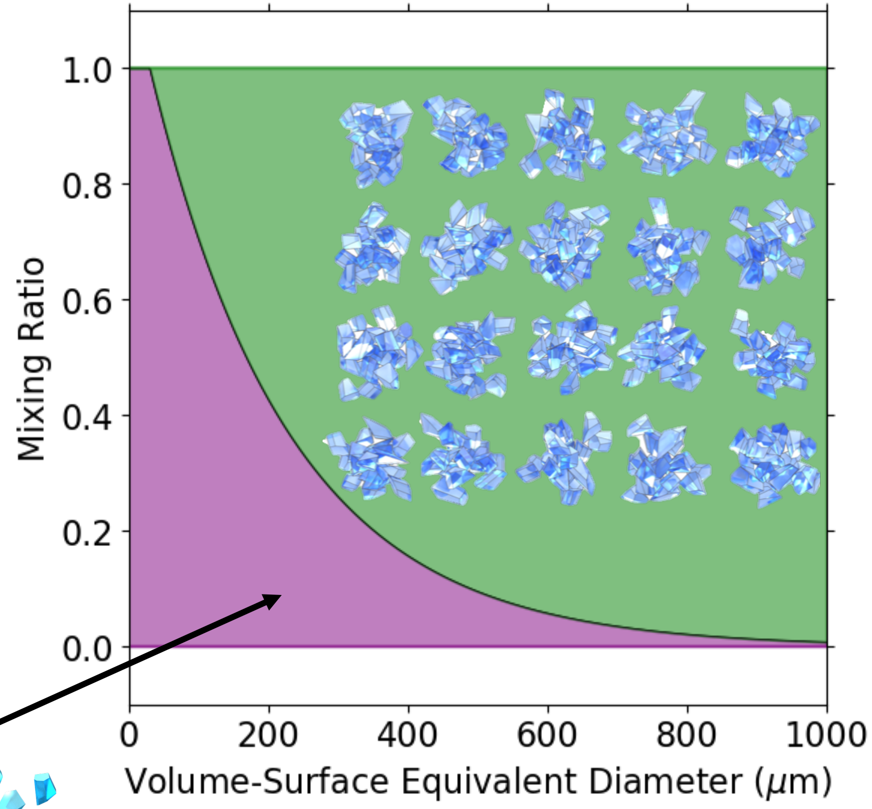
- PGOM provides more enhanced and accurate backscattering calculations for moderate and large size parameters.
    - PGOM-enhanced calculations only applied to backscattering region ($> 170°$) of IGOM calculations to reduce computational burden.

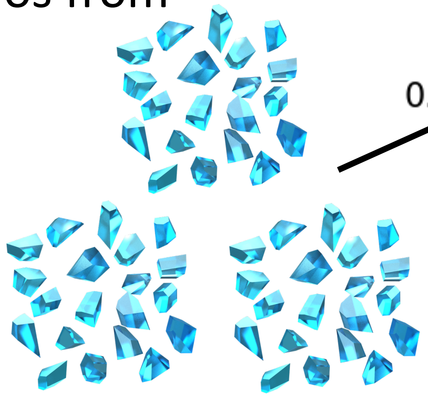


Preliminary Version of New THM

- 60-particle irregularly-shaped single particle ensemble.
- 20-particle irregularly-shaped 20-column aggregate ensemble.
- Uses D_{VA} size characterization instead of D_{max}.
- All P_{11} components of phase matrix have been enhanced in the backscattering region.
- IITM-calculated single-scattering properties for size parameters < 25
- Uses same size-dependent, continuous mixing ratios from 2nd version of THM.
- Current THM version 3 database:
  - 42 wavelength bins (0.2 – 20 µm).
  - 59 size bins (2.0 – 1000.0 µm).

$$f_{aggregate} = 1.0 - f_{single}$$



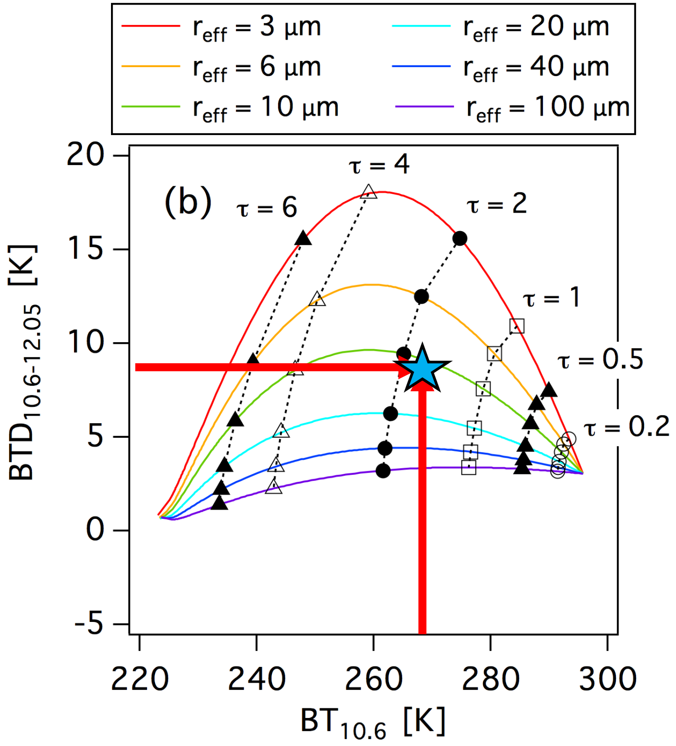


$$f_{single} = \begin{cases} e^{-0.005(D_{VA}-30)}, & D_{VA} \geq 30 \\ 1, & D_{VA} < 30 \end{cases}$$

Active–Passive Consistency Check

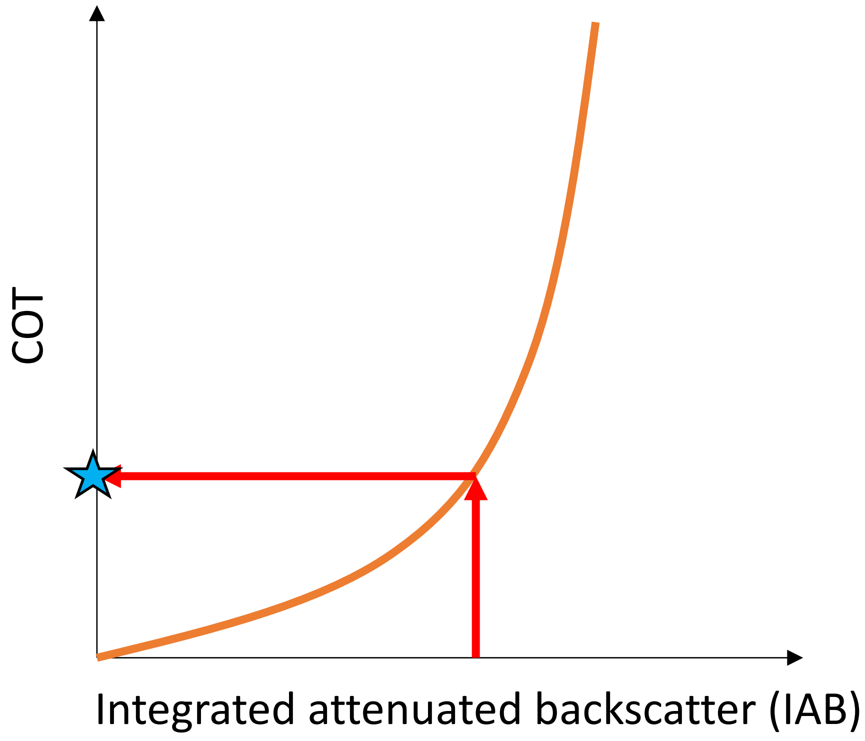
IIR based retrievals

- Split-window technique (Inoue, 1987)
  - IIR level-2 track product
  - MERRA-2 atmospheric profile
  - MODIS SST product

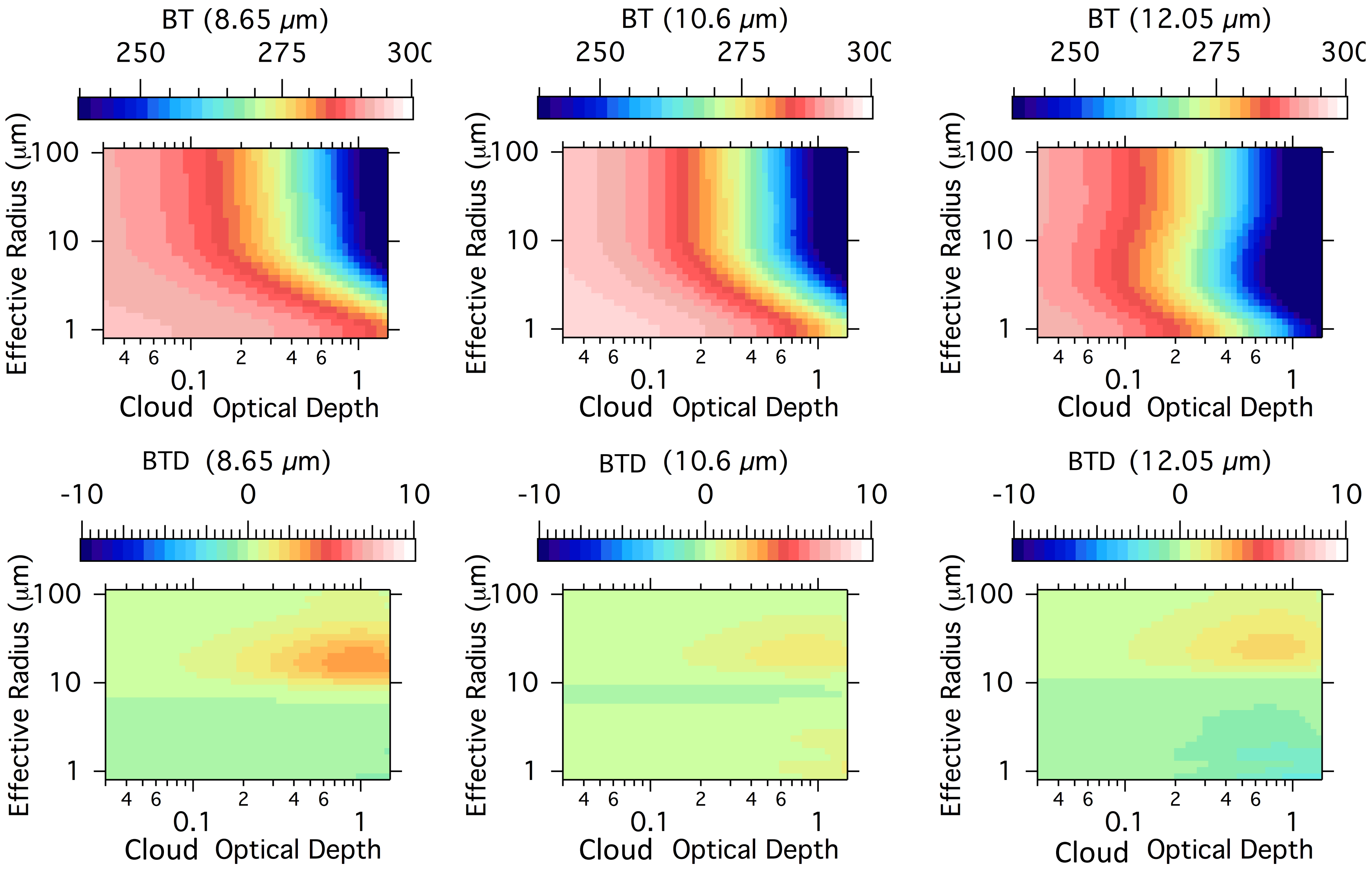


CALIOP based retrievals

- IAB–COT approach (Ding et al., 2016)
  - CALIOP level-2 Cloud layer product
  - Monte Carlo backscattering simulation
  - Effective radius of 30 μm is assumed.



IIR radiative transfer simulations

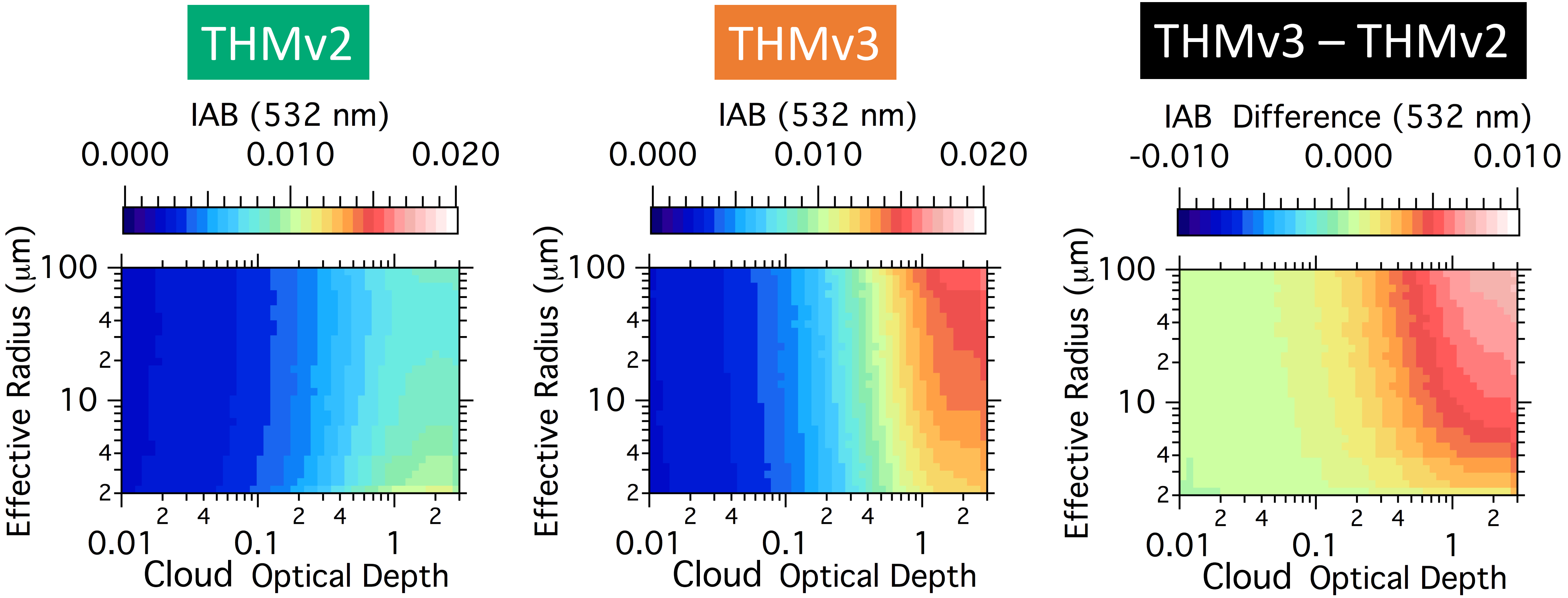


THMv3

THMv3 – THMv2

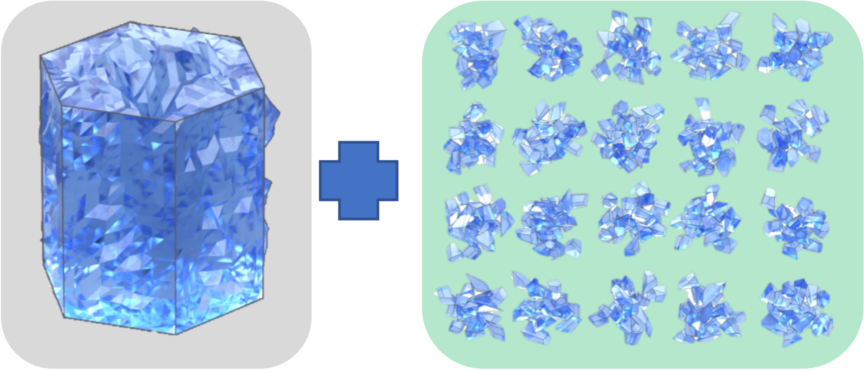
- Improved THM has a small impact on thermal infrared bands.

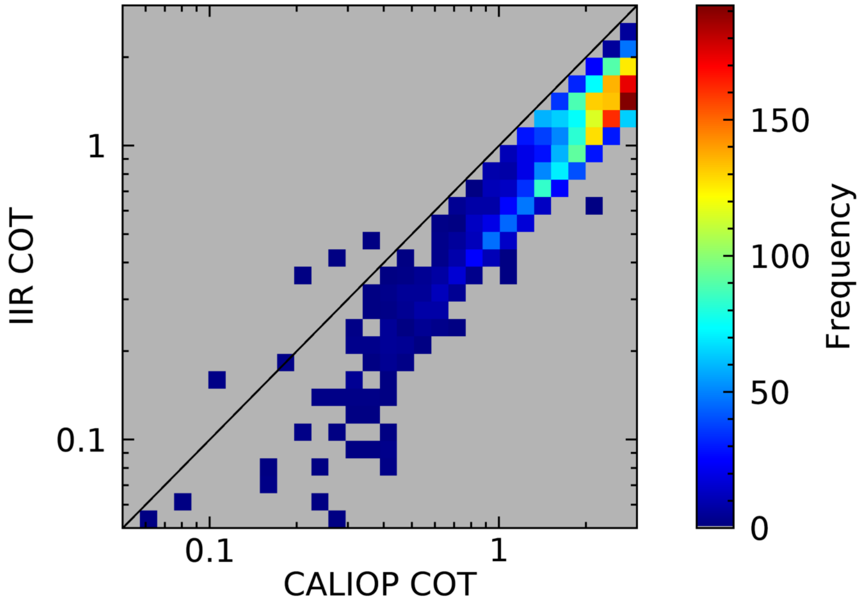
CALIOP radiative transfer simulations

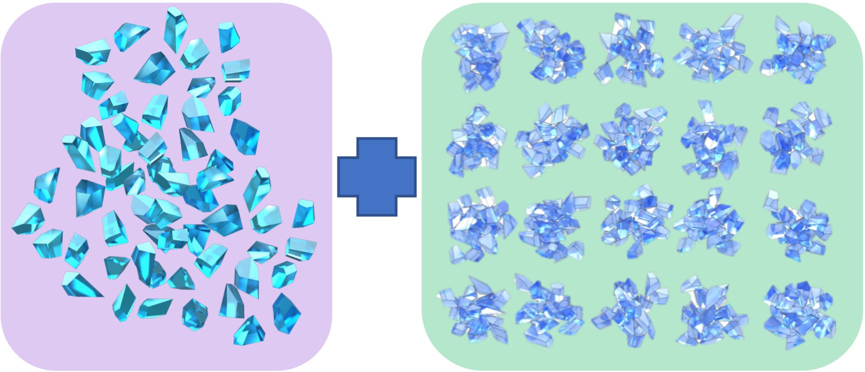


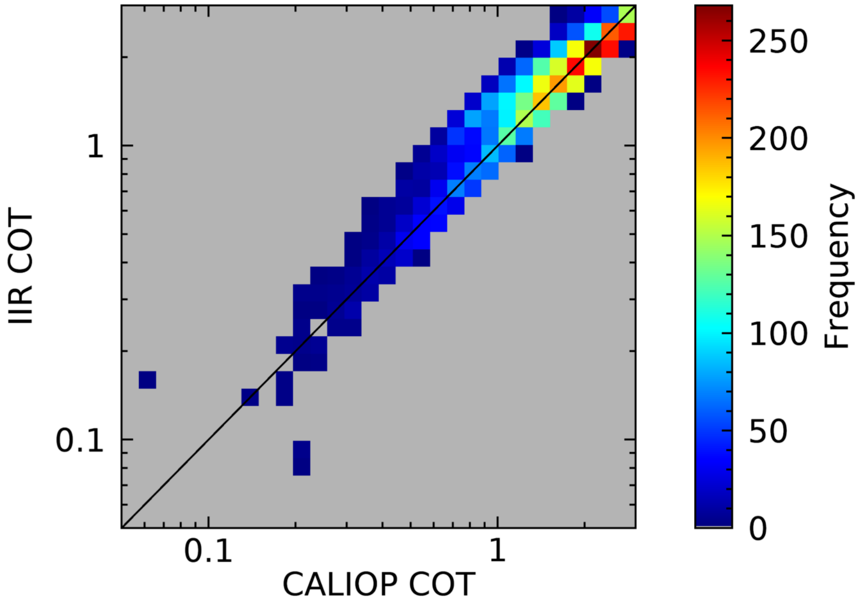
- The improved THM leads to substantially stronger backscatter.
- The theoretically derived lidar ratio ranges from 30–35 sr for effective radii 10–80 μm.

Active–Passive Consistency Check









Improved THM has reasonably robust backscatter.

→ Achieves Active–Passive consistency in COT retrievals.

Deliverables:

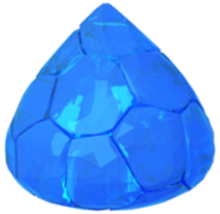
	Improved THM (preliminary version for test/validation purpose)	Improved THM (final version)
Wavelength	42 bins (0.2 – 20 μm)	470 bins (0.2 – 200 μm)
Size	59 bins (2.0 – 1000.0 μm)	189 bins (2.0 – 10000.0 μm)

Development of the optical properties of graupel and snow for the Langley Radiative transfer model

Ice mass ratio (IMR) is smaller than 1 for graupel and snow particles. Previously, this effect was not been taken into consideration in light scattering computations.

$$\text{IMR}=\frac{\text{Mass of ice in a bulk shape}}{\text{Mass of the bulk shape fully filled with ice}}$$

- IMR=0.2
- D_m=17 mm

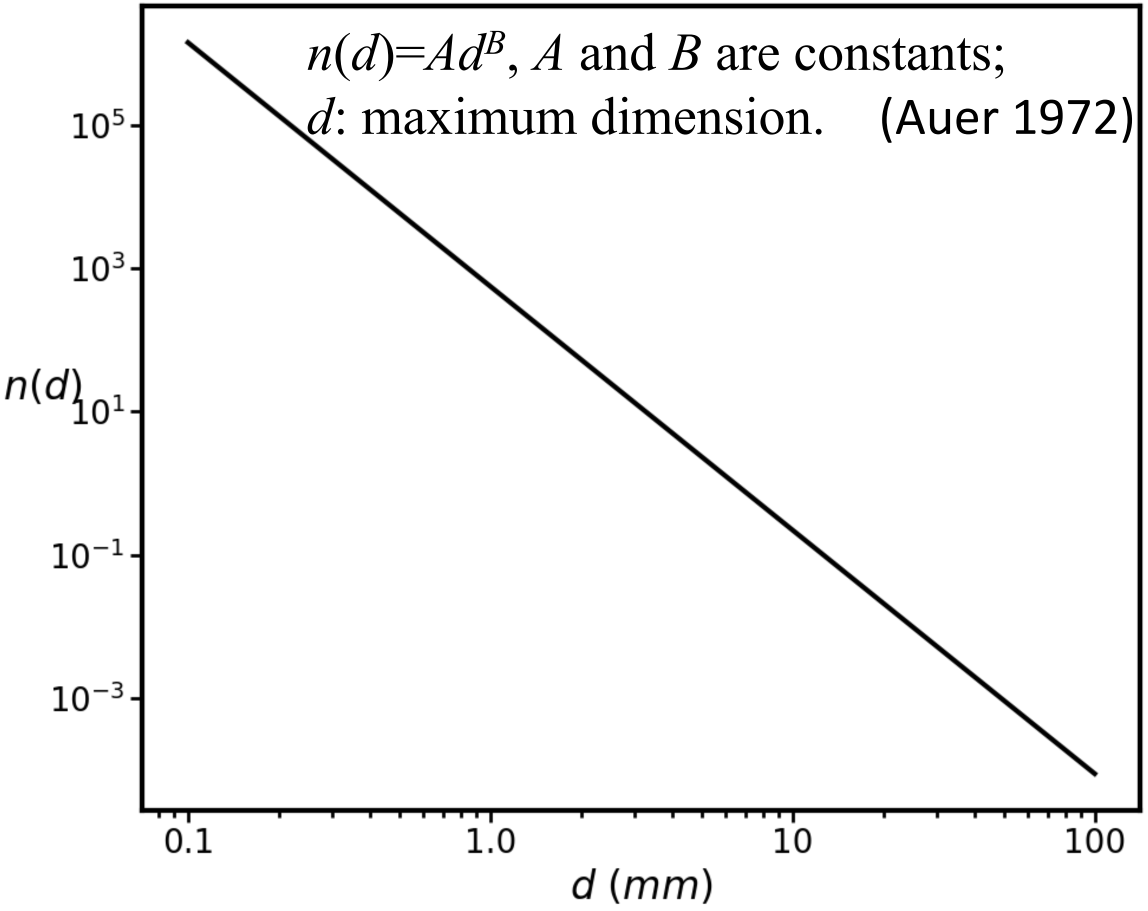


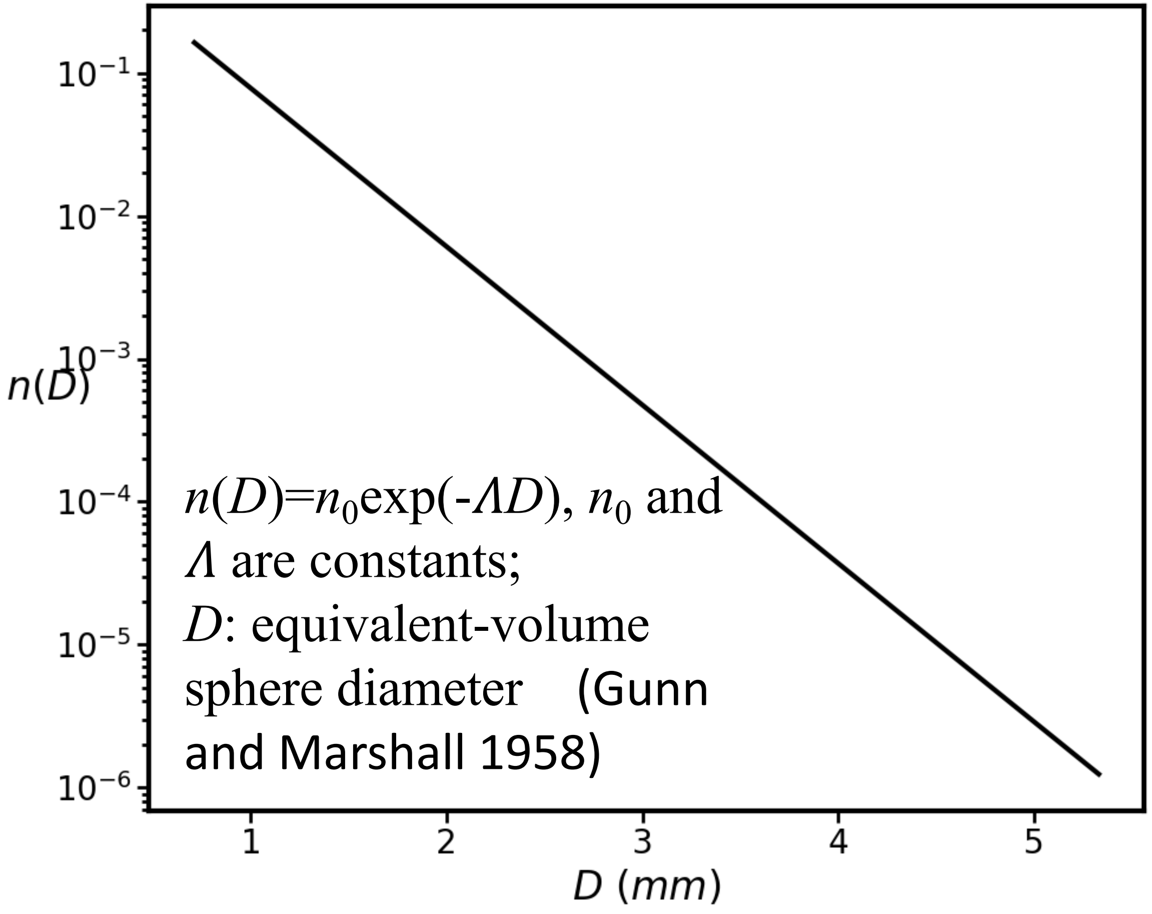
- IMR=0.9
- D_m=28 mm

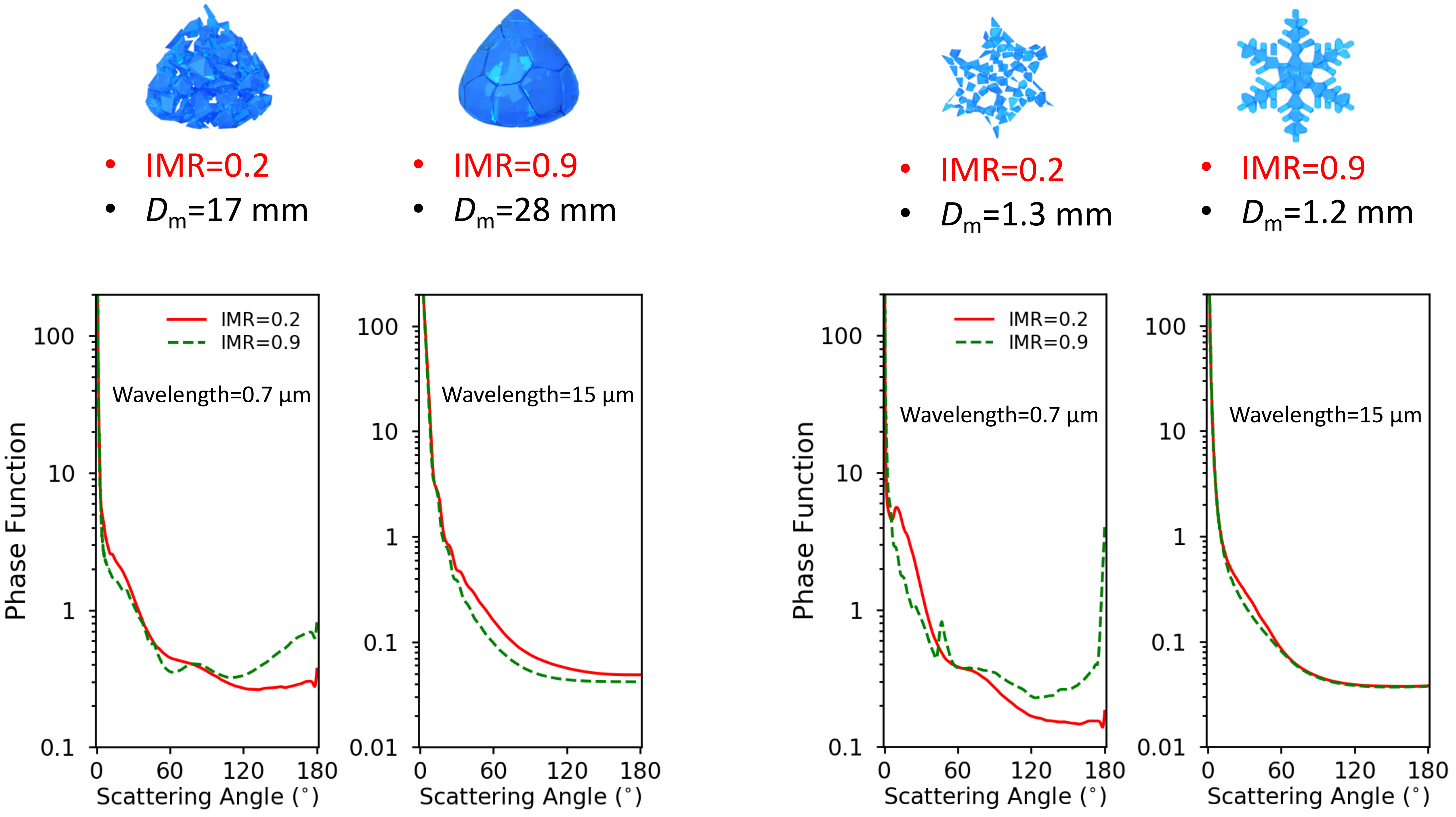
- IMR=0.2
- D_m=1.3 mm

- IMR=0.9
- D_m=1.2 mm

D_m: median-mass equivalent-volume sphere diameter

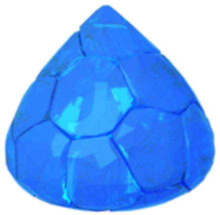






IMR=0.2
D_m=17 mm
IMR=0.9
D_m=28 mm
IMR=0.2
D_m=1.3 mm
IMR=0.9
D_m=1.2 mm
IMR=0.2
IMR=0.9
Wavelength=0.7 μm
Wavelength=15 μm
Wavelength=0.7 μm
Wavelength=15 μm
Phase Function
Scattering Angle (°)

- IMR=0.2
- D_m=17 mm

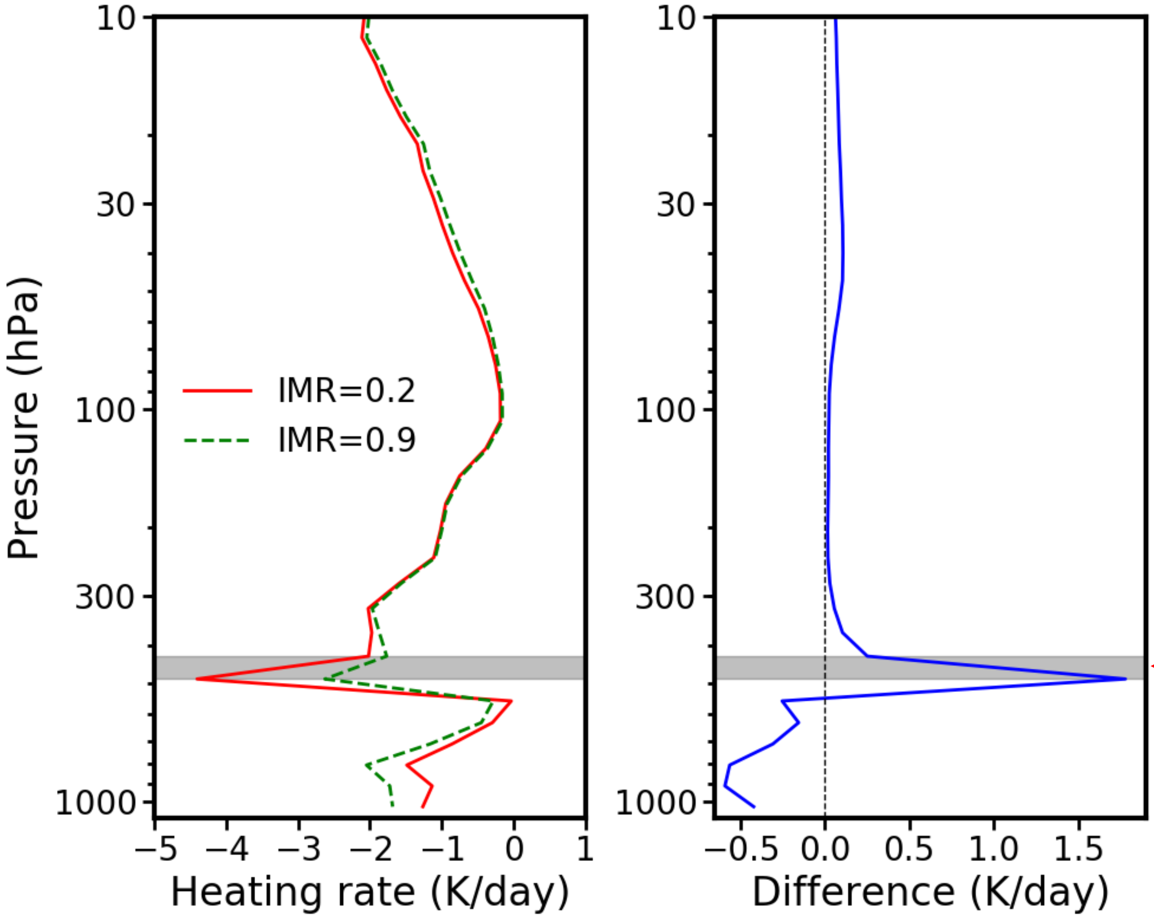


- IMR=0.9
- D_m=28 mm

RRTM heating rate simulations

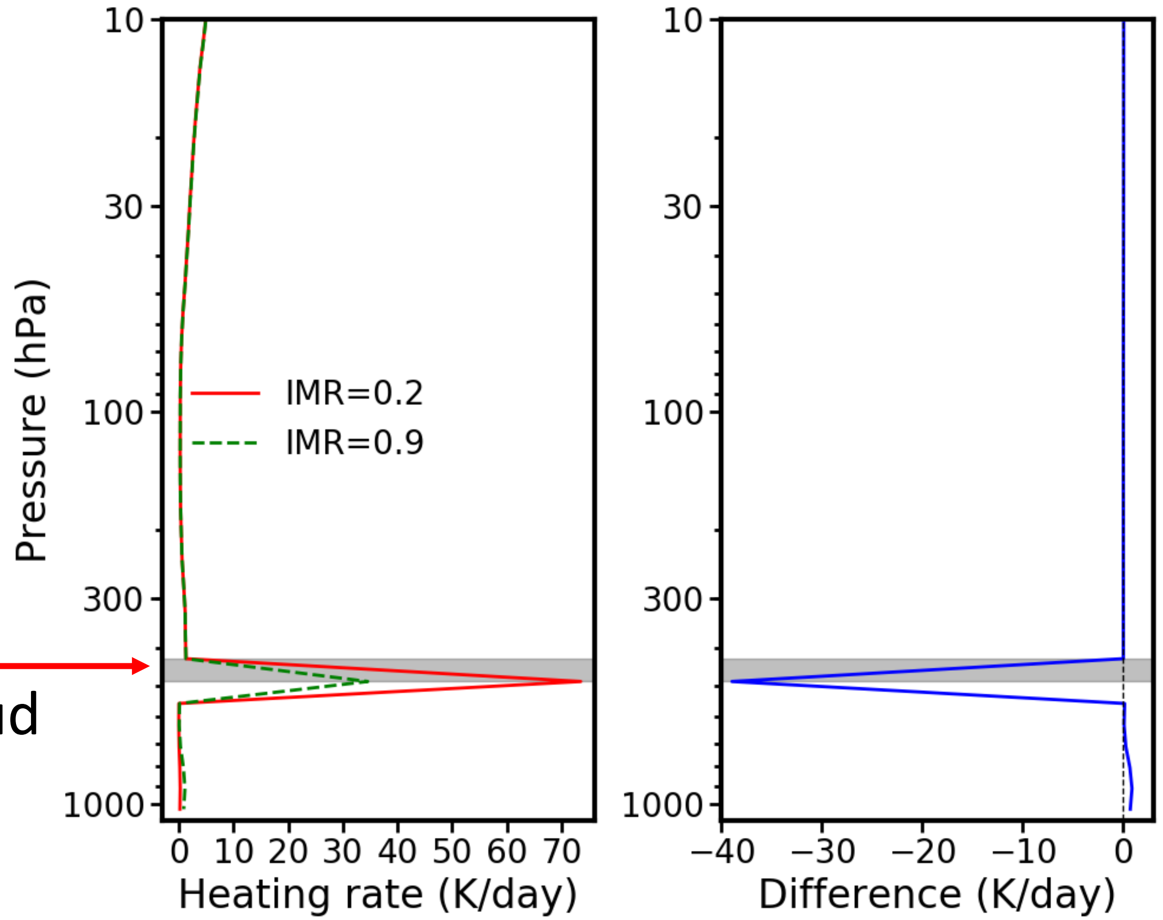
- Ice water path (IWP): 400 g/m^2;
- The graupel is taken as a cloud layer;
- 16-stream DISORT
- Shortwave (SW) and longwave (LW) .

LW heating rate



cloud

SW heating rate



- IMR=0.2
- D_m=1.3 mm

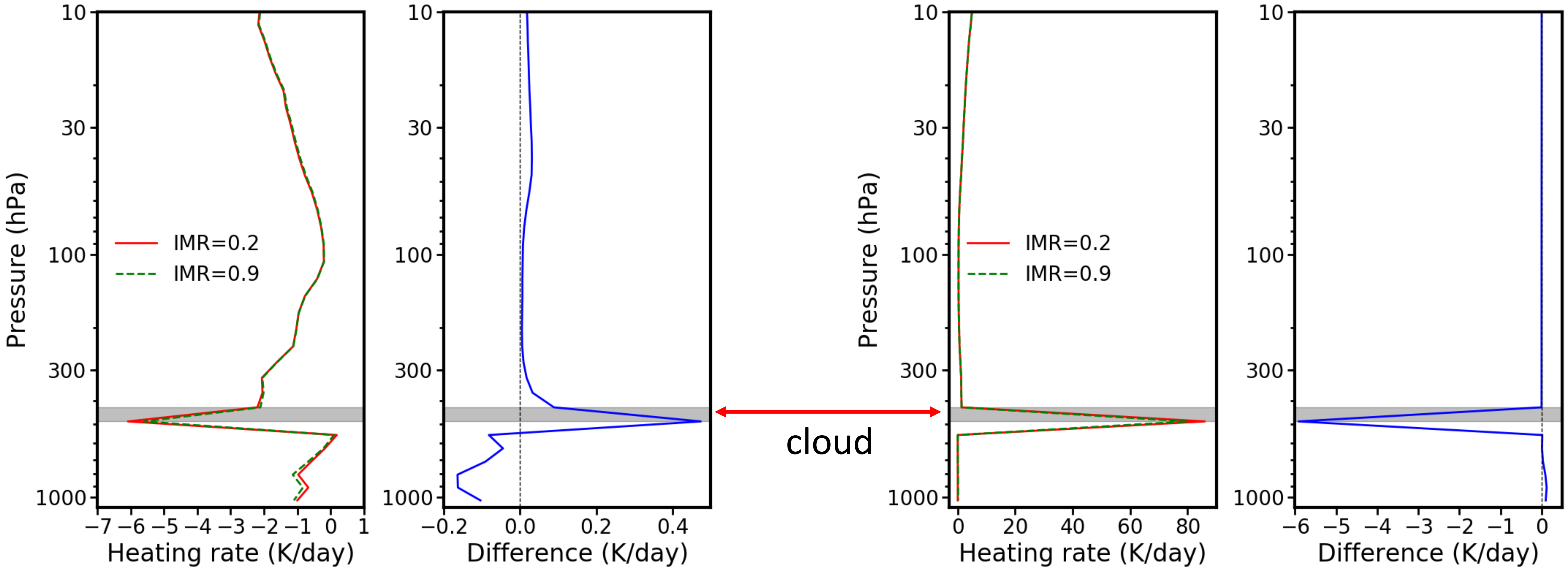
- IMR=0.9
- D_m=1.2 mm

RRTM heating rate simulations

- Ice water path (IWP): 400 g/m^2;
- The graupel is taken as a cloud layer;
- 16-stream DISORT
- Shortwave (SW) and longwave (LW) .

LW heating rate

SW heating rate



Summary

- Substantial progress has been made, toward improving the two-habit model (THM) for computation of the optical properties of ice clouds

- A preliminary database will be completed by September 2020 for
  - Test/validation in remote sensing applications
  - Test/validation in radiative parameterization for broadband radiative transfer simulations

- A comprehensive database that will require a tremendous amount of computational effort will be completed next year

- Will develop spectrally resolved optical properties of graupel and snow for radiative parameterization for the Langley radiative transfer model